DESIGN AND REVIEW OF STRUCTURES FOR PROTECTION FROM FALLOUT GAMMA RADIATION

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DISCLAIMER

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF BASIC CHARTS FOR SHIELDING ANALYSIS

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

LIST OF EXAMPLES

CHAPTER I

FALLOUT DESCRIPTION

1a Formation of Fallout

The detonation of a nuclear weapon near the ground causes large quantities of earth and debris to be melted and vaporized. This material mingles with the fission products in the rapidly rising fireball. As this material cools, it forms particles, many of which act as carriers of the radioactive sources created by the fission process. These particles vary in size from a fine powder to large grains (Tables 1A & 1B) and may ascend to altitudes of 15 miles or more. The larger particles fall back to the earth's surface within about one day ("early fallout"), but some remain aloft far longer ("delayed fallout"). Since delayed fallout offers no shielding problems, the term "fallout" as used in this manual will pertain to early fallout* only.

1b Regional Distribution of Fallout

Significant amounts of fallout do not arrive outside the blast area earlier than about one-half hour after an explosion. From then on, it begins to cover an increasingly large area and may eventually blanket thousands of square miles. Substantially all of the early fallout has reached the ground within one day after the explosion. At any given location, however, the elapsed time between the arrival of fallout and the cessation of deposition may be a matter of hours. (Sec. 2c).

The pattern of early fallout depends largely on the type, size, and detonation position of the weapon involved and the meteorological conditions for the first day after the explosion. In areas where the patterns of two or more weapons overlap, the hazard is increased; and in a massive nuclear attack on the United States, much of the country would be covered by dangerous radioactive contamination. Some idea of the extent of fallout from a single nuclear burst is shown by the patterns illustrated in Fig. 1.

It should be noted that it is not possible to predict, with any real certainty, the amount of fallout at any given location. It is therefore reasonable to make conservative assumptions in most shielding analyses.

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*Also termed "close-in" or local fallout.

TABLE 1A--PARTICLES OF EARLY FALLOUT

Size	Diameter, microns	Fall velocity,* fpm	Fall time,* hours	Travel distance,* miles
Silt (dust)	50	40	34	Over 300
Very fine sand	100	160	8	120
Fine sand	200	640	2	30
Medium sand	400	2500	½	Under 10

*Approximated by Stokes Law under standard atmospheric conditions and assuming spherical particles, specific gravity 2.65, uni-directional wind 15 mph, initial altitude of particle 80,000 ft. and no turbulence in atmosphere. For sand size particles, the Stokes Law underestimates fall time. For example, the fall time for medium sand might be closer to 1-1/2 hours than 1/2 hour.

TABLE 1B--PARTICLES OF DELAYED FALLOUT

Size	Diameter microns	Fall velocity fpm	Fall time	Travel Zone
Generally invisible to naked eye	0.1 to 1.0	Not Applicable	2 wks. to 6 months	Travels in Troposphere
	0.01 to 0.1		6 months to 2 yrs.	Travels in Stratosphere

1c Local Distribution of Fallout

Of particular interest in shielding problems is the actual distribution of the fallout particles on and around a structure.

Flat, built-up roofs with parapets probably collect and retain more fallout than any other roof type; smooth, sloping roofs without dormers or monitors collect and retain the least. However, in the case of sloping roofs, fallout may collect in the eavestroughs where it may remain for some time. The effects of wind, rain, and snow on fallout deposition on various roof types are only qualitatively known; therefore, unless special conditions indicate otherwise, fallout is usually assumed to cover roof surfaces uniformly according to their horizontal projections (Fig. 2). In the case of smooth sloping roofs without eavestroughs, much of the contamination may be blown off the roof and a judgment factor may be applied to account for this situation. (Sec. 4b).

Fallout particles also may settle on window sills, ledges, niches, grooves, etc. Except in unusual circumstances, however, these contaminated areas are not considered in shielding analyses. Further, it is usually assumed that no significant amounts of fallout enter the structure.

The fallout deposition in the area around a structure may be of equal or greater importance than that on the structure itself. Among the factors affecting the local distribution of fallout around a structure are the type and relative location and height of nearby buildings; its position relative to geographic features such as hills, depressions, bodies of water, etc; and the nature of the surrounding ground such as paved or unpaved, wooded or cleared, etc. For convenience, the effects of these various factors will be discussed later. (Chapter IX). In general, fallout will be assumed to cover the area surrounding the structure uniformly.

Once fallout is on the ground, it may be further redistributed by the action of wind, rain, and snow. This is termed "weathering" and its effects are so variable and complicated that they receive only limited consideration in this manual. (Sec. 9b). However, in certain problems the influence of weathering, as well as operational decontamination, must be recognized.

1d Radioactivity from Fallout

The radioactivity carried by fallout particles is of three different kinds; viz., alpha, beta, and gamma.

Alpha and beta emitters may be dangerous if they are ingested through contaminated food, water, or air; but from the shielding standpoint, they offer no problem. Alpha particles cannot penetrate the external layer of skin and, although beta particles can produce burns on unprotected skin, clothing may afford reasonable protection. However, gamma radiation is very penetrating and can penetrate the body causing serious damage to living tissue (Sec. 2b). Its relationship to other electromagnetic radiations is shown in Fig. 3.

CHAPTER II

FALLOUT GAMMA RADIATION

2a Units of Gamma Radiation

Radioactivity is often expressed in units of "curies." This is defined as the quantity of any radioactive material having 3.7×10^{10} disintegrations per second. Source density, or the amount of radioactivity associated with a contaminated area, is given in terms of curies per unit area.

Another unit of interest, the "Mev" (millions of electron volts), is used to indicate the energy of the radiation emitted from a source (Sec. 2e). Sometimes reference is also made to the "kev" (kilo, or thousands of electron volts).

Probably the most widely used unit in shielding analyses is that used to measure the dose of radiation to which an object is exposed. This is the roentgen (r). Exposure dose rates are expressed as roentgens per hour (r/hr).

To approximately relate these three units (curie, Mev, and roentgen), use may be made of the following equation:

$R = 6nCE$, where

R = Dose rate (r/hr) 1 ft away from a point source*

n = Average number of photons per disintegration

C = Radioactivity (curies) of source

E = Energy (Mev) of radiation

EXAMPLE: What is the dose rate 1 ft away from a 10 curie point source of Co^{60}? Assume the average energy per disintegration is 1-1/4 Mev and that $n = 2$.

$R = 6 \times 2 \times 10 \times 1\text{-}1/4$, or

R = 150 r/hr Answer

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*For distances other than 1 ft see Sec. 2f.

2b Biological Effects

Since the objective of shelters is to protect life and health, some idea of the biological effects of gamma radiation is necessary in shielding work. It should be clearly understood that much remains to be learned about the reaction of humans to radiation exposure, but certain generalities may be made and they are summarized in Table 2A*. Naturally, the effect of a given amount of radiation on a specific individual would depend to a large degree on his age, state of health, past radiation history, etc. It is also important to note two other items which relate to Table 2A. First, exposure doses received over a long period of time may be less harmful than those received in a few days. Second, long-range effects of exposures such as decreased resistance to diseases, blood changes, shortened life span, etc., are not included under "Probable Effects."

The information in Table 2B is presented to acquaint engineers with the fact that, in general, radiation casualties are a tremendous medical burden. Even those persons who have received lethal doses may linger for days or weeks before dying.

2c Variation of Dose Rate with Time

From the time of their formation when the nuclear explosion occurs, fission products begin to decay; that is, their radioactivity decreases. The rate of decay is extremely rapid shortly after the explosion, but later it is relatively slow and the process may be said to continue indefinitely. An approximate curve (Fig. 4, Curve A) has been found to describe this decay process for a single nuclear explosion.

A somewhat less accurate, but far more convenient statement of the decay process is -- for every sevenfold increase in time after the explosion, there is a tenfold decrease in dose rate.

For example, three hours after a nuclear explosion, measurements are taken in an area where fallout is no longer accumulating on the ground; they indicate a dose rate of 50 r/hr. Assuming no weathering effects, what would be the predicted dose rate 18 hours later (21 hours after the explosion)?

The ratio of elapsed times (21/3) is 7; therefore, the predicted dose rate would be 1/10 of the three hour dose, or about 5 r/hr. The scaling factor from Curve A of Fig. 4 for an elapsed time ratio of 7 is about 0.095, and the dose rate 21 hours after the explosion would be 0.095 x 50 r/hr or 4.8 r/hr. The advantage of Curve "A" is that it can be used for any time ratio, not just factors of 7.

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*See "The Biological Effects of Atomic Radiation, Summary Reports," National Academy of Science - National Research Council, Washington, D. C., 1960.

TABLE 2A--PROBABLE ACUTE EFFECTS OF GAMMA RADIATION ON HUMANS

Short-term whole-body exposure, roentgens	Probable Effect
0 to 100	No obvious effects
100 to 200	Some sickness
200 to 300	Sickness and some deaths
300 to 600	Severe sickness and many deaths
Over 600	Few survivors

TABLE 2B--PROBABLE LENGTH OF ILLNESS OF HUMANS RECEIVING LETHAL ACUTE DOSES OF GAMMA RADIATION

Short-term whole-body exposure, roentgens	Probable Length of Illness (Time between exposure and death)
up to 1000	2 weeks to 1 month ("Bone Marrow" death)
1000 to 2000	1 week to 2 weeks ("Gastro-intestinal" death)
Over 2000	1 day to 3 days ("Central Nervous System" death)

To calculate the dose accrued in an interval of time Curve B of Fig. 4 may be used. A convenient rule for determining accrued dose is that a person remaining for a very long time (months or more) in a contaminated area beginning one hour after the explosion (H + 1) would receive a total accrued dose numerically equal to about five times the dose rate measured at H + 1.

For example, one hour after a nuclear explosion, a monitor inside a shelter notes that his instrument reads 8 r/hr and also finds out that fallout is no longer accumulating outside. If the shelter occupants were removed to a "clean" area 49 hours after the attack, how much dose would they have accrued while in the shelter? How much dose would they accrue if they remained in the shelter indefinitely?

From Curve B of Fig. 4, the scaling factor for an elapsed time ratio of (49/1) is 0.53. This means that 53% of the total accrued dose would be accumulated between the 1st and 49th hour. Since the total accrued dose would be about five times the H + 1 dose rate (5 x 8r/hr) or 40r, the shelter occupants would accrue 53% of 40r or about 21r while in the shelter.

An additional variable which affects the variation in dose rate at a given point is the deposition time of the fallout. Studies indicate that for a given point, the fallout initially collects on the ground at such a rate that the dose rate generally increases from the time of arrival until a given time (about one or more hours later) when it reaches a maximum. It is only later, when the deposition has ceased, that the dose rate tends to follow the decay law mentioned earlier in this section. Thus, the accumulated dose at a given point could be largely accrued in the time period preceding the time when the decay law may be appropriate and therefore estimations of total accumulated dose by the decay law alone could be very misleading.

As pointed out earlier, all of the above information could be applied only to fallout from a single nuclear explosion. Fallout arriving at a given point from different ground zeros could alter the situation markedly. Therefore, the use of Fig. 4 and similar rules relating to the decay of fallout gamma radiation should be used only for broad planning purposes.

2d Propagation

Gamma radiation may be considered as a continuous stream of photons (energy "packets"). These packets travel from their source, the "excited" (radioactive) nuclei of atoms until they interact with the electrons of other atoms.* Each photon that is incident on a barrier may - (1) pass through the barrier without

*Interactions with the nuclei are not important over the range of fallout gamma radiation energies.

interaction; (2) be absorbed in the barrier (photoelectric absorption); or (3) be scattered in the barrier (Compton effect). (Fig. 5). The probability of an interaction depends on the barrier thickness and material (Sec. 3a) and on the photon energy (Sec. 2e).

In photoelectric absorption all of the energy of the photon is imparted to the electron. In the scattering process, the photon loses only part of its energy to the electron. After scattering, however, the photon travels in a different direction and at a lower energy than it did before the interaction. An important consequence of this effect is that radiation may emerge from a barrier at very different directions from the original direction of the incident radiation. The scattering effect is illustrated in Fig. 6.

In Fig. 6a, detector No. 1 receives direct radiation while detector No. 2 receives virtually no radiation. In Fig. 6b, detector No. 1 is shown receiving scattered radiation at various positions. Detector No. 2 in Fig. 6b receives radiation which is said to be back-scattered. The proportion of radiation back-scattered is termed albedo.

2e Energy

Since the probability of an interaction between a photon and an atomic electron depends on the photon energy, the penetration of gamma radiation through a barrier is also dependent on the gamma energy. In general, the higher the energy of the radiation, the greater its ability to penetrate. An idea of this effect may be gained from Figs. 11 and 12 which indicate the comparative attenuation occurring in concrete barriers of varying thicknesses from a cesium 137 source (0.67 Mev) and a cobalt-60 source (1.25 Mev).

Since the various sources of radioactivity (radioisotopes) in fallout have different characteristic energies, fallout gamma radiation is made up of a series of energies. There will be more radiation of some energies than others. This distribution of energy is referred to as the energy spectrum.

During the decay processes the relative number of different radioisotopes is constantly changing and consequently the energy spectrum of the fallout is constantly varying. In effect, this means that the protection offered by a shelter varies with time (Fig. 7). To avoid this complication in shielding calculations, the energy spectrum of fallout which exists about one hour after the explosion is used in this manual. This spectrum includes energies up to several Mev. Present studies indicate that this is a conservative, but realistic assumption.

2f Variation of Dose Rate with Height

A point source in a vacuum emits radiation equally in all directions, and dose rate is inversely proportional to the square of the distance from this type of source. A uniformly contaminated plane of infinite extent can be assumed to be made up of a collection of point sources. As the distance of a detector above a uniformly contaminated plane is changed, the dose rate from each point source that makes up the contamination varies inversely with its distance from that source. If the detector height is doubled, the dose rate from the point source directly below the detector decreases by a factor of 4, but the dose rate from a more distant point source hardly changes. This, coupled with the effect of air absorption from the more distant sources, results in an expression for the variation in dose rate with height above a plane source that is very different from the inverse square law for a point source. This expression is presented graphically in Fig. 8*.

The variation in dose rate shown in Fig. 8 may also be applied to cleared areas. That is, the slant distance from the detector to the circumference of a cleared circle in a uniformly contaminated plane may be substituted for the height on this chart. Although this curve is strictly applicable only to the case of an air-to-air interface, the substitution of an earth-to-air interface probably does not radically alter its shape. Finally, it should be noticed that the reduction factors obtained from Fig. 8 are identical to those obtained from Chart 2 for $X_w = 0$ psf.

2g Directional Distribution

If a detector is placed at the center of a sphere which has point sources uniformly distributed over its surface, the measured dose rate will depend only on the number of sources per unit area (source density). A collimated detector placed at the center of this sphere would indicate the same dose rate in whatever direction it is pointed.

Now suppose that the sources are not uniformly distributed over the spherical surface; then the collimated detector reading will depend upon its orientation. For example, if the source density is greater near the equator of the sphere, the detector will indicate a higher dose rate when pointed in that direction (Fig. 9). The polar diagram in this figure indicates a relative dose rate measured by the detector when it is pointed in different directions in a vertical plane, i.e., it graphically represents the directional distribution.

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*Effects d e to ground roughness are discussed in Sec. 9b.

Next, consider the situation when a collimated detector is located over a uniformly contaminated plane (Fig. 10). When pointed vertically downward, it sees a particular source density equal to that of the contaminated plane. However, as it is tilted, the source density perpendicular to the source-detector line, increases. Hence, the dose rate will be higher. As the detector approaches a horizontal position, however, the effect of air absorption becomes greater since the radiation from distant sources has a greater chance of interaction in the air. This effect blunts the polar diagram of the directional distribution which is extremely peaked in the horizontal direction (Fig. 10). It might be assumed that as the detector is tilted upward from the horizon its reading would be zero since it does not "see" any sources. This is not the case, however, since although no direct radiation is seen, the air itself scatters some radiation. The air-scattered radiation (skyshine) is a manifestation of the Compton effect. The upper (shaded) portion of the polar diagram in Fig. 10 gives an indication of its relative magnitude.

CHAPTER III

BARRIER SHIELDING

3a General

The shielding effectiveness of various barrier materials can be measured by the relatively simple arrangement illustrated in Fig. 11. Here a narrow (collimated) beam from a radioactive source is directed through a series of apertures to a detector. Under ideal narrow beam conditions, only unscattered radiation reaches the detector. Detector readings are taken for various thicknesses of barrier and compared to readings taken without the barrier. The ratio of the reading with a given barrier thickness to the reading without any barrier is called the transmission factor, or attenuation.

The results from a narrow beam attenuation experiment are also shown in Fig. 11. For convenience, the lower scale is given in terms of the thickness of a concrete barrier, and the upper scale as "mass thickness," by the weight of the barrier material per unit surface area, which is commonly expressed as pounds per square foot (psf).

In this manual, mass thickness will be the only property of the barrier material used in shielding calculations. Its chemical composition is not important in the energy range associated with fallout gamma radiation and with common shielding materials which have relatively low atomic numbers. Common shielding materials would include soil, concrete, brick, stone, etc. (Sec. 5c).

Shielding materials with high atomic numbers such as lead are, on a "pound for pound" basis, somewhat more effective. For example, a particular shield may require about 305 psf of concrete, while only 240 psf of lead is necessary; but the cost of the concrete would be far less. Unfortunately, no simple rule can be strictly used to relate the shielding "effectiveness" of ordinary construction materials and substances such as lead. As a rule of thumb, however, it may be said that 8 psf of lead is equivalent to 10 psf of concrete. This rule does not apply to steel or other structural metals.

The relationship of source energy and attenuation is indicated in Fig. 11. As mentioned earlier (Sec. 2e), the higher the energy of the source, the less the attenuation offered by a barrier of a given mass thickness. Note, however, that this effect is less pronounced in the thinner barriers.

In many shielding situations the radiation striking the barrier is not collimated, and some of the radiation scattered in the barrier can reach the detector. In broad beam studies, an attempt is made to account for the scattered radiation by starting with a point source and detector separated by a barrier of fixed thickness and increasing by steps, the area of the barrier "seen" by the detector (Fig. 12). At first, the dose rate will increase due to radiation scattered in the barrier. When the dose rate no longer increases with the area, broad beam conditions are said to exist.

If an uncollimated detector is located adjacent to the barrier, then broad beam conditions exist, provided that the length and width of the barrier are greater than several mean paths.* A common method of evaluating the shielding at such a detector is to correct the narrow beam attenuation by a factor called the build-up factor, F_b, which depends on the source energy and geometry. In practice, its use has been restricted to simple source geometries. In this manual the narrow beam attenuation and build-up factor are not considered separately, but only their product, which is called the barrier factor.

In shelter shielding analyses, the detector is not usually located adjacent to any barrier. In general, therefore, broad beam conditions do not exist. In a sense, the geometry factor may be regarded as a correction for the absence of broad beam conditions.

3b Shielding from Contaminated Planes

The source geometry most frequently encountered in shelter calculation is that of a contaminated plane. For simplicity, only three basic situations involving a plane source and a barrier have been considered (Chart 1). A description of these three cases and a definition of the barrier shielding curve corresponding to each is given below:

Case 1 - Fallout is deposited on top of a horizontal barrier (Fig. 13a). This is termed "Fallout on Horizontal Barrier." The corresponding barrier shielding curve gives the ratio of the dose rate immediately under the barrier to that at 3 ft above an infinite contaminated plane of the same source density.

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*A mean free path may be defined as the thickness of material which reduces the intensity of direct radiation by a factor of "e", the base of natural logarithms.

Case 2 - Fallout is deposited on a horizontal plane on one side of a vertical barrier (Fig. 13b). This is termed "Fallout Adjacent to a Vertical Barrier." The corresponding shielding curve gives the ratio of the dose rate on the shielded side of the barrier to that on the unshielded side of the barrier. Both dose rates refer to a height of 3 ft above the plane*.

Case 3 - Fallout is deposited around the barrier but does not lie directly on it (Fig. 13c). This is termed "Fallout Adjacent to Horizontal Barrier." The corresponding shielding curve gives the ratio of the dose rate at a detector immediately under the center of the barrier to a detector shielded from direct radiation that is located immediately above the center of the barrier; that is, both detectors receive only radiation which has been scattered at least once in the air above the horizontal barrier.

*Barrier factors for other heights are found in Chart 2.

CHAPTER IV

GEOMETRY SHIELDING

4a Solid Angle

Evaluation of geometry shielding effects frequently requires the calculation of the solid angle subtended at the detector by a radiating surface. Solid angle is a measure of how much of the field of view of a detector is occupied by the radiating surface. If the surface is very close to the detector, it occupies a large portion of the field of view and the solid angle is correspondingly large. The same surface located farther away from the detector would subtend a smaller solid angle.

To visualize the solid angle subtended by an area at a detector, place the detector at the center of a sphere and connect the periphery of the area with the detector (Fig. 14). Solid angle is defined as the area A (measured in steradians) projected on the surface of the sphere of radius r. One steradian is equal to r^2, consequently, the entire surface of a sphere is 4π steradians. In shielding work it is more convenient to deal with a "solid angle fraction", ω, which is the fraction of the area of a hemisphere that is subtended by the radiating surface, i.e., $\omega = \frac{A}{2\pi r^2}$.

For a detector located along the axis of a circular radiating surface (Fig. 14a), it is rather simple to compute the solid angle fraction; but for rectangular areas, the problem is somewhat more complicated. In this manual, however, a simplified procedure has been adopted which requires the calculation of two ratios and the use of Chart 3. When the detector is located along the central axis of a rectangular surface (Fig. 14b), these two ratios are as follows:

eccentrictiy ratio, $e = \text{width/length} = W/L$

normality ratio, $n = 2 \times \text{perpendicular distance from plane/length} = \frac{2Z}{L}$

Detailed procedures and sketches illustrating solid angle calculations are presented in Sec. 5d and Example 1.

4b Directional Response

Although the solid angle fraction subtended at a detector by a radiating surface gives a good indication of the geometry shielding effect, it is far more accurate to also consider the directional distribution associated with the radiating surface. The combined effect of both the solid angle fraction and the directional distribution is termed "directional response." It is used to assess how much radiation a given finite surface is contributing to a

detector, or how much radiation is reaching a detector through a given aperture.

The directional response for an overhead contaminated plane is closely related to the mass thickness of the barrier between the plane and the detector. Thus, Chart 4, which has as its parameters solid angle fraction and mass thicknesses gives the combined effect of both the directional response (geometry effect) and the barrier effect (Example 3).

The directional response from the ground contamination surrounding a detector is calculated for 3 separate cases of directional distribution. The sketches on Chart 5 indicate the relationship between the contaminated surface and the solid angle subtended at the detector for these 3 cases which are:

(a) The direct case, G_d

(b) The skyshine case, G_a

(c) The scattered case, G_s

Notice also the sketch on Chart 6, where it is shown how the height of the detector is considered in addition to the solid angle fraction below the detector plane to determine the directional response, G_d (Sec. 6d).

When analyzing overhead apertures, only the directional response need be calculated and this is presented as Case 1 on Chart 10. Of course, in this case the overhead mass thickness is assumed to equal zero. Under such conditions and even for slightly greater mass thicknesses, there may be a marked contribution from skyshine. Case 3 on Chart 10 presents the directional response of skyshine through an overhead aperture. The total response at a detector beneath an aperture would normally be the sum of the responses for Cases 1 and 3. There are cases, however, such as sloping sky lights where the contamination will presumably not collect over the aperture and under these circumstances Case 3 alone would be used. To account for the skyshine contribution through greater overhead mass thicknesses, a correction should be made to the results obtained from Chart 4. Table 3 may be used for this correction.

TABLE 3

"Skyshine" Correction for Chart 4

(Reduction Factors for Combined Shielding Effects,
Roof Contribution)

Overhead Mass Thickness, X_o (psf)	Contaminated Roof	Decontaminated Roof
0	Use Chart 10	Use Chart 10
25	1.10	0.10
50	1.08	0.08
100	1.04	0.04
200	1.01	0.01

4c Combining and Differencing Directional Responses

In the previous section, mention was made of directional responses, G_d, G_a, and G_s. To actually solve a shielding problem, however, use is made of a "combining" or "differencing" technique. Example 2 illustrates the basic idea of these processes. Note that if the two solid angle fractions are both above or below the detector plane, the directional responses are subtracted. If, however, one solid angle fraction is above and the other below the detector plane the directional responses are added. Notice that all solid angle fractions are referred to the same vertical axis. The method of weighting directional responses for wall-scattered and non-wall-scattered radiation will be discussed in the next section.

4d Weighting Directional Responses

In a typical shielding problem both direct and scattered radiation reaches a detector. The mass thickness of the wall largely determines the relative amounts of direct and scattered radiation and Chart 7 indicates quantitatively this effect. For the purpose of this section, the term "non-wall-scattered" refers to radiation which passes through the walls without interaction, regardless of whether or not it has been scattered in the air outside of the structure. In other words, both G_d and G_a are considered to be directional responses for "non-wall-scattered" radiation. The term "wall-scattered" refers to radiation scattered in the walls of the structure, that is, G_s is the directional response for "wall-scattered" radiation.

Weighting directional responses for both non-wall-scattered and wall-scattered radiation which reaches a detector after passing through a vertical surface may be done as follows:

(1) Calculate the directional response for the structure assuming walls of "zero" mass thickness (this is as if the detector were located in an area cleared of contamination and only "non-wall-scattered" radiation is detected. G_d and G_a on Chart 5 may be used for this purpose.

(2) Calculate the directional response for the structure assuming walls of very great mass thickness and that only wall-scattered radiation is detected. Curve G_s of Chart 5 may be used for this purpose.

(3) Weight steps (1) and (2) by the use of a suitable proportion which accounts for the scattering associated with the actual mass thickness of the walls. Chart 7 may be used for this purpose.

Detailed procedures and sketches illustrating weighting techniques are presented in Example 4, which also shows how barrier effects are taken into account.

4e Shape Factor

Present studies indicate that a detector located between two very thick walls of infinite length and height would have a lower reading than one at the center of a square tower with walls of the same mass thickness even if both structures were located in smooth contaminated planes of equal source density and extent. These studies have also shown that the dose rate in the square structure would be about 1.4 times the one measured in the "two-wall" structure. Rectangular buildings would logically fall between 1.0 and 1.4. This effect has been accounted for in a shape factor (E) which is applied to the geometry factor of the calculations for wall-scattered radiation. Chart 8 may be used to determine the appropriate shape factor.

CHAPTER V

PRELIMINARY CALCULATIONS

5a Introduction

The location of the position to be analyzed is called the "detector position," or simply the "detector." In this manual, the term "protection factor" is the coefficient which, when multiplied by a dose rate in a protected position (shelter area), will equal the dose rate outside. This outside dose rate is that which would be indicated by a detector 3 ft above the center of a smooth, uniformly contaminated area of infinite extent.

For convenience in calculation, the reciprocal of the protection factor, called the "reduction factor," is used. Reduction factors, expressed as decimals, can be added when combining the effects of fallout on the roof over a detector and fallout on the ground around a detector. For example, the roof contribution at a given detector may be 0.015 and the ground contribution at this same point 0.010. The sum of these, 0.025, would be the total reduction factor. The protection factor in this case would be the reciprocal of 0.025, or 40.

Theoretical and experimental work indicates that when following procedures outlined in this manual, protection factors should be rounded off to not more than two significant figures. For thinner barriers, mass thickness is usually given to the nearest pound per square foot (psf); but for thicker barriers, the nearest 5 psf is commonly used. In practice, barriers of metal are usually reported to the nearest 1/8-in. thickness; barriers of masonry (concrete, brick, etc.) to the nearest inch; and earth barriers to the nearest 2 in.

5b Functional Equations

The complexity of the equations which must be used to make shielding analyses is so great that analytical solutions are not appropriate. Instead, it is necessary to make use of what is termed functional equations. The simple analytical expression $y = x^2 + 3x + 6$ can be rewritten as $f(x) = x^2 + 3x + 6$ to describe the value of this function. The notation $f(x)$ merely indicates that the value of interest is a function of x. Using the equation expressed above, $f(2) = 2^2 + 3 \cdot 2 + 6$ or $f(2) = 16$.

In shielding analyses, however, functional equations are generally represented by graphical expressions. For example, consider Case 1 of Chart 1, which graphically expresses barrier

reduction factors as a function of mass thickness. In this particular case, B_o (X_o) has its values determined by the curve which graphically describes this function. The following expressions can be written using functional notation:

$$B_o \text{ (80 psf)} = .038$$

$$B_o \text{ (150 psf)} = .0055$$

In other words, the barrier reduction factor for roof contamination is a function of the mass thickness of the barrier between the contamination and the detector. If the barrier mass thickness, X_o, is 80 psf, then the barrier reduction factor would be .038; if X_o = 150 psf, then B_o = .0055.

Many of the expressions used in shielding analyses are functions of two variables. For example, the barrier reduction factors for walls is a function not only of the mass thickness of the wall, but also of the detector height above the contaminated plane. In functional notation, this would be described by the expression B_w (X_w,H) which is graphically presented in Chart 2. As an example, B_w (150 psf, 90 ft) = .01. This system of functional notation is useful since the various procedures for making a shielding analyses can be concisely described by them. Table 4 summarizes the general procedures using functional equations.

The examples also use this functional notation and it is useful to compare the various steps in the examples with the appropriate functional equation of Table 4.

5c Mass Thickness

The term mass thickness has been introduced in Sec. 3. Its determination is usually a simple arithmetic problem. For solid, uniform barriers, it is merely the product of the unit weight of the material and the thickness of the shield, that is, X = U x t, where X = mass thickness, psf; U = unit weight, pcf; and t = barrier thickness, ft (Example 3b). Sometimes this formula is written $X_\theta = U \times t \times \sec \theta$; "$\theta$" being the angle of incidence of the incoming radiation. In this case, X_θ may be called the "oblique" mass thickness. The charts in this manual, however, have been constructed to intrinsically take into account the various angles of incidence associated with a given situation so that in almost all cases only the "normal" (sec θ = 1) mass thickness need be used.

The mass thickness of a barrier with contiguous layers is the sum of its component layers, $X = X_1 + X_2 \ldots + X_n$. (Example 3b).

TABLE 4

BASIC FUNCTIONAL EQUATIONS FOR SHIELDING ANALYSES

The following functional equations apply to rectangular structures with a roof of uniform construction and walls of uniform construction. They apply to structures located in a smooth, level, uniformly contaminated plane of infinite extent. The detector is assumed to be located at the center of the structure for equations (1) through (7); and, in addition, at sill level for equation (5). In general, $R_f = (1) + (5) + (6) + (7)$ and $P_f = 1 \div R_f$.

Roof Contribution:

$$(1)\quad C_o(\omega_o, X_o) + [C_o(\omega'_o, X_o) - C_o(\omega_o, X_o)]\,\frac{B_w(X_i, H_f)}{B_w(0, H_f)}$$

Ground Contribution through adjacent walls, windowless case:

$$(2)\quad B_w(X_e, H)\, B_w(X_i, 3')\, G_g$$

$$\text{where } G_g = [G_s(\omega_\ell) + G_s(\omega_u)]\, S_w(X_e) E(e)$$

$$+ [G_d(\omega_\ell) + G_a(\omega_u)]\,[1 - S_w(X_e)]$$

Ground Contribution through ceiling, windowless case:

$$(3)\quad B_w(X_e, H_u)\, B_w(X_i, 3')\, B'_o(X'_o)\, G_g$$

$$\text{where } G_g = [G_s(\omega'_u) - G_s(\omega_u)]\, S_w(X_e)\, E(e)$$

$$+ [G_a(\omega'_u) - G_a(\omega_u)]\,[1 - S_w(X_e)]$$

Ground Contribution through floor, windowless case:

(4) $B_w (X_e, H_\ell) B_w (X_i, 3') B_o (X_f) G_g$

where $G_g = [G_s (\omega'_\ell) - G_s (\omega_\ell)] S_w (X_e) E (e)$

$+ [G_d (\omega'_\ell, H) - G_d (\omega_\ell, H)] [1 - S_w (X_e)]$

Ground Contribution through adjacent walls, window case:

(5) $C_g + (C_a - C'_a) P_a$ or $C_g + (C_a - C'_a) Az_a$

where C_g is equation (2) above

and $C_a = B (X_i, 3') [G_a (\omega_a)] B_w (X_e = 0, H)$

and $C'_a = B_w (X_e, H) B_w (X_i, 3') [G_s (\omega_a) S_w (X_e) E (e) +$

$G_a (\omega'_a) [1 - S_w (X_e)]]$

Ground Contribution through ceiling, window case:

(6) $[C_g] (100\% - A_p) + [C'_g] A_p$

where C_g is equation (3) above with X_e

and C'_g is equation (3) above with $X_e = 0$ psf, i.e.

$B_w (X_i, 3') B'_o (X'_o) [G_a (\omega'_u) - G_a (\omega_u)] B_w (X_e = 0, H)$

Ground Contribution through floor, window case:

(7) $[C_g]$ (100% - A_p) + $[C'_g]$ A_p

where C_g is equation (4) above with X_e

and C'_g is equation (4) above with X_e = 0 psf, i.e.

$B_w (X_i, 3') \; B_o (X_f) \; [G_d (\omega'_\ell, H) - G_d (\omega_\ell, H)] \; B_w (X_e = 0, H)$

Ground Contribution through perpendicular passageways:

(8) a. 1st Corridor, $A_v (\omega_1)$

b. 2nd Corridor, $0.1 \; \omega_2 \; R_f$ (1st)

c. 3rd Corridor, $0.5 \; \omega_3 \; R_f$ (1st) R_f (2nd)

d. nth Corridor, $0.5 \; \omega_n \; R_f$ (1st) R_f (2nd) R_f (3rd) ..... R_f (n-1)

Roof Contribution through shafts, including skyshine:

(9) Vertical shaft, $A_h (\omega_1) + A_a (\omega_1)$

For subsequent R_f's see equations (8)b, (8)c and (8)d above.

TABLE 5

LIST OF SYMBOLS

List of Symbols for Shielding Analysis

A . . . . . . Area (sf).

A_a . . . . . Directional response for skyshine radiation through horizontal aperture.

A_h . . . . . Directional response for direct radiation through horizontal aperture.

A_p . . . . . Percent of apertures in wall relative to total wall area.

A_v . . . . . Directional response for direct and skyshine radiation through vertical aperture.

Az . . . . . Azimuthal sector

B . . . . . Barrier reduction factor for plane isotropic source.

B_e . . . . . Barrier reduction factor for exterior wall construction.

B_i . . . . . Barrier reduction factor for interior wall construction.

B_o . . . . . Barrier reduction factor for overhead construction.

B'_o . . . . . Barrier reduction factor for barrier immediately overhead.

B_w . . . . . Barrier reduction factor for wall construction.

B_{ws} . . . . . Barrier reduction factor for wall-scattered radiation (mutual shielding case only).

C_g . . . . . Reduction factor accounting for combined barrier and geometry shielding effects; ground contribution.

C_o . . . . . Reduction factor accounting for combined barrier and geometry shielding effects; overhead (roof) contribution.

D . . . . . Perpendicular distance between vertical plane and detector (ft).

e . . . . . Eccentricity ratio = W/L.

E . . . . . Shape correction factor for wall-scattered radiation.

F_e . . . . . Effective fetch (ft).

G . . . . . Geometry reduction factor

LIST OF SYMBOLS

List of Symbols for Shielding Analysis

G_a. . . . . .Directional response for skyshine radiation.

G_d. . . . . .Directional response for direct radiation.

G_g. . . . . .Geometry reduction factor for ground contamination.

G_s. . . . . .Directional response for wall-scattered radiation.

H . . . . . . .Height of detector plane above contaminated plane (ft).

H_f. . . . . .Fictitious height = 13Xo (ft). Also added height to account for ground roughness.

L . . . . . . .Length of structure (ft).

n . . . . . . .Normality ratio = 2Z/L.

P_a. . . . . .Perimeter ratio of apertures.

P_f. . . . . .Protection factor.

P_r. . . . . .Perimeter ratio.

P_s. . . . . .Barrier reduction factor for point isotropic source.

R_f. . . . . .Reduction factor.

r_e. . . . . .Effective radius (ft).

S_w. . . . . . Percent of emergent radiation scattered in wall barrier.

t . . . . . . .Barrier thickness (ft).

U . . . . . . .Unit weight of barrier (pcf).

W . . . . . . .Width of structure (ft).

W_c. . . . . .Width of finite contaminated strip (ft).

X_b. . . . . .Mass thickness of exterior basement walls (psf).

X_e. . . . . .Mass thickness of exterior walls (psf).

TABLE 5 (CONTINUED)

LIST OF SYMBOLS

List of Symbols for Shielding Analysis

X_f. . . . . .Mass thickness of floor construction (psf).

X_i. . . . . .Mass thickness of interior walls (psf).

X_o. . . . . .Total overhead mass thickness (psf).

X_o'. . . . . .Mass thickness of barrier immediately overhead (psf).

X_w. . . . . .Wall mass thickness (psf).

Z . . . . . .Perpendicular distance between horizontal plane and detector (ft).

ω_l(omega) . .Solid angle fraction below detector plane.

ω_o(omega) . .Solid angle fraction subtended by roof.

ω_s(omega) . Solid angle fraction below mid-wall height for limited field in mutual shielding cases.

ω_u(omega) . .Solid angle fraction above detector plane.

ω_1,ω_2, etc. .Solid angle fraction in first, second, etc. leg of passageway or shaft.

TABLE 5 (CONTINUED)

LIST OF SYMBOLS

Other Symbols Used in Text

Bev. . . . . Billion electron volts.

C . . . . Radioactivity in curies.

e . . . . Base of napierian logarithms.

E . . . . Energy of radiation.

ev . . . . Electron volts.

f . . . . Function of x.

Fb . . . . Build-up factor in inches.

fpm. . . . . Feet per minute.

Kev. . . . . Kilo electron volts.

Mev. . . . . Millions of electron volts.

pcf. . . . . Pounds per cubic foot.

psf. . . . . Pounds per square foot.

R_o . . . . Dose rate behind a barrier of thickness, $t = 0$ (roentgens per hour).

R_t . . . . Dose rate behind a barrier of thickness, t (roentgens per hour).

r . . . . Roentgens, r/hr, roentgens per hour.

T . . . . Time elapsed since formation of fission products.

u . . . . Linear absorbtion coefficient.

θ . . . . Angle at which a given path of radiation strikes a barrier measured from the perpendicular to the barrier.

Barriers with varying mass thickness such as floor joist systems, hollow masonry walls, etc. are usually calculated as uniform barriers of equivalent mass thickness. For example, a 3 in. concrete floor slab resting on concrete beams 4 in. wide by 8 in. deep which are 16 in. on centers would have its equivalent mass thickness computed as follows:

EXAMPLE: X (floor slab) = 148 pcf x 3/12 ft = 37 psf.

X (floor beams) = 148 pcf x 8/12 ft = 98 psf, but

the beams only occupy 4/16 of the floor surface area so that they contribute 98 psf x 4/16 = 24 psf to the mass thickness of the floor system.

X (floor system) = 37 psf + 24 psf = 61, say <u>60 psf</u> Answer

This type of calculation is often not necessary because it may be sufficiently accurate to assume that the weights per unit surface area for the various types of roof, floor, and wall construction as given in standard engineering tables are equivalent to the mass thickness of the construction. This assumption is predicated upon the detector being some distance from the barrier. It is obvious that a detector just under a floor slab would be less protected from roof sources than another just under a floor beam. In most cases, if the detector is five or more feet away from the nearest roof, floor or wall, the equivalent mass thickness can be used. In unusual situations, where it appears necessary to account for radical variations of mass thickness in a given barrier, the techniques presented for compartmentalized structures can be used. (Chapter VIII).

Mention should be made of a common error in estimating mass thickness of soil by always assuming it has a unit wieght of 100 pcf. Depending on type, water content, compactive effort, etc., soil may have an "in-place" unit weight of from less than 90 pcf to over 130 pcf. Attention should be given the selection of the proper unit weight of a soil barrier.

5d Solid Angle Fractions

As mentioned in Sec. 4a, the calculation of a solid angle fraction can be readily accomplished with the use of Chart 3. This chart indicates the solid angle fraction of a plane rectangular area subtended at a detector located along a central axis which is perpendicular to the plane. Example 1a illustrates this calculation. When the detector is located at the corner or side of a rectangle, the solid angle fraction can still be easily calculated by taking

1/N times the solid angle fraction as determined by an area N times as large. For example, if a detector is located above (or below) the corner of a rectangular plane, it is considered to be at the center of a fictitious rectangle four times as large; a solid angle fraction, ω', is then calculated using Chart 3, and the desired solid angle fraction, ω, is taken to be equal to $\omega'/4$. This type of calculation is shown in Examples 1b and 1c.

In analyses involving a passageway or shaft with one or more changes of direction, the solid angle fraction is used directly as a multiplier. In the case of a passageway, the solid angle fraction is referred to a horizontal axis (i.e., the distance "Z" is measured along the perpendicular from the detector to a vertical plane); in shaft problems the solid angle fraction is referred to a vertical axis. Functional equations 8 and 9 in Table 4, which are used in Example 9, indicate this application of the solid angle fraction.

The solid angle fraction is also used directly as a parameter in determining the reduction factor for combined shielding effects, in problems involving roof contribution (Sec. 4b and Chart 4). The use of the solid angle fraction in roof contribution problems is illustrated in Examples 3 and 4.

There is one other situation in which the solid angle fraction is used directly. This is the problem involving fallout particle pile-up around basement areas. Detailed treatment of this type of problem is presented in Chapter IX.

5e Directional Responses

In Sec. 4b, six directional response functions were mentioned; three -- G_d, G_a, and G_s are represented on Chart 5 and will be discussed in this section. The others -- A_v, A_h, and A_a are shown on Chart 10 and will be treated in Chapter VII. On both charts the solid angle fraction is the only input information required.

When using Chart 5, the solid angle fraction must be referred to a vertical axis; that is "Z" must be the perpendicular distance of the detector to a horizontal plane. It should be noted that Chart 5 indicates the response functions for radiation coming from directions between the detector plane and the "sides" of a fictitious pyramid (or cone) which describes the solid angle fraction and not from within the solid angle fraction itself. (Fig. 15). Thus, the process of differencing and combining response functions from both above and below the detector plane is simplified.

Example 2 illustrates the methods of combining and differencing directional responses. Note that the heavily shaded portion in Example 2a represents the directions (below the detector plane) from which radiation paths are not excluded; that is, all radiation emerging from the wall, whether direct or scattered, must come from within this zone to be accounted for by the detector response function. A similar statement could be made about the lightly-shaded portion above the detector plane. However, in Example 2b, we see that the unshaded portion above the detector plane represents the directions from which radiation paths are not excluded. Note the lower shaded portion in Example 2b; by ignoring contributions from directions within this zone, it has been tacitly assumed that no radiation penetrates the earth surrounding the structure and arrives at the detector after passing through the belowground portions of the wall. In most cases, this "lip" contribution is negligible, but when the contamination is piled up against the foundation wall, this contribution cannot be neglected, and it is treated as a special problem in Chapter IX.

One final note -- it is important to remember that directional responses are combined or differenced and not solid angle fractions. For example, if the solid angle fractions themselves (Steps 4 and 5 of Example 2) were differenced, the result would be (.81 - .57) or .24, and the corresponding response function for wall-scattered radiation would be, from Chart 5, equal to .45. This, of course, is incorrect. As can be seen in Step 8, the differenced G_s should equal .15. In this case differencing solid angle fractions instead of response functions results in an error by a factor of 3.

CHAPTER VI

SIMPLE STRUCTURES

6a Simple Underground Shelter

Perhaps the simplest shielding analysis to perform is that of an isolated underground blockhouse without interior partitions. The calculation is illustrated in Example 3a, which can be either a design or review procedure. The case illustrated is a design problem which requires the determination of the total overhead mass thickness for a given protection factor; the dimensions of the structure being fixed. The solution is simply a matter of finding the solid angle fraction of the contaminated roof subtended at the detector ($\omega_u = 0.7$) and the appropriate reduction factor ($R_f = .0002$). With these two parameters the required mass thickness is found on Chart 4. This procedure is illustrated in Fig. 16a. In a review problem, the overhead mass thickness and the solid angle fraction are known and the appropriate reduction factor would be found as shown in Fig. 16b. Notice that skyshine has not been taken into account in Example 3a because in this case, and in most others where underground shelters are concerned, it is generally insignificant. It should also be noted, that even geometry effects are not important in this problem, and frequently they are unimportant in other underground shelter problems. To illustrate the importance of geometry effects in this particular design problem one could compare the overhead mass thickness required if the barrier shielding curve of Case 1, Chart 1, was used in lieu of Chart 4. From barrier shielding effects alone, the required mass thickness would be about 300 psf. When geometry effects are considered, as in Example 3a, the required overhead mass thickness is 295. The difference, 5 psf, is roughly equivalent to 1/2" of earth which would be considered insignificant for most practical cases.

This is not to say, however, that geometry effects are not important in all underground shelter problems. For example, it may be desired to place an arch shelter underground with a relatively light cover over the crown. In this case the geometry factors could be quite critical since the contribution from the thinner portions of the barrier are confined to a relatively small solid angle fraction. An analysis by zones such as that illustrated in Example 3c indicates how the geometry factors are utilized.

The functional equation which describes this calculation for the central zone and the two adjacent zones is equation (1) in Table 4. Note, however, that since there is no interior partition,

$B_w(X_i,H_f) = 1$. Also note that the dose contributions from other zones are found from the differencing procedure illustrated by the second term in equation (1), i.e. $C_o\ (X_o,\omega_o') - C_o\ (X_o,\omega_o)$.

6b Simple Aboveground Shelter

One means for making a quick approximation of the mass thicknesses required in the walls and roof of a simple aboveground blockhouse is to consider barrier effects alone. Further, it is sometimes useful to allow one-half the dose contribution to come from the contaminated roof, and the other half from the contaminated ground. For example, if a small aboveground concrete blockhouse is to have a protection factor of 10, the required reduction factor would be 0.1; and it could be assumed that half of this (.05) would come through the roof, while the other half (.05) came through the walls. Then, using the barrier shielding effects (Chart 1), the roof mass thickness, X_o, (Case 1) would have to be about 70 psf, and the wall mass thickness X_w (Case 2) would have to be about 130 psf. In other words as a first approximation, this particular blockhouse would require about a 6-inch roof slab and an 11-inch wall for a protection factor of 10. The next step in the design would be to include the geometry effects for the particular blockhouse in question. This requires a review procedure as shown in Example 4.

The calculations illustrated in Example 4 are straight forward even though the symbolization may exaggerate the difficulty of the problem to the novice. The general approach is merely to calculate the appropriate eccentricity and normality ratios (e's and n's) and then from Chart 3 determine the upper and lower solid angle fractions, ω_u and ω_l, indicated on the sketch. Next the directional responses (G_a, G_d, and G_s) are determined from Chart 5 for the radiation reaching the detector from above and below the detector plane. It is also necessary to determine the fraction of emergent radiation which is scattered by the wall (S_w) from Chart 7 and the factor which accounts for the shape of the structure (E) from Chart 8.

With this data available, it is a matter of simple arithmetic to determine the total ground geometry reduction factor (G_g) which is composed of the ground geometry reduction factor for wall-scattered radiation, G_s calculated in Step 6; and the ground geometry reduction factor for non-wall-scattered radiation, G_d and G_a; calculated in Step 8. (Sec. 4d). This total ground geometry reduction factor must, in turn, be multiplied by the appropriate barrier shielding factor, B_w from Chart 2 in order to find the reduction factor for the total combined shielding effects for ground contribution. This is done in Step 9. The roof contribution, which has already been discussed in

Example 3, is shown in Step 10 without consideration being given skyshine. If skyshine were considered (Table 3), Step 10 would be closer to .036 than .034 -- not a particularly significant difference in this problem. Usually only a quick mental check of Table 3 is necessary to determine if skyshine through the roof warrants consideration. The total reduction factor which is the sum of the reduction factors for the combined shielding effects of both roof and ground contributions is found in Step 11. It is important to note that the S_w and E factors are applied only to the response functions for wall-scattered radiation (Step 6). Since S_w indicates the fraction of emergent radiation which has been scattered in a wall of given mass thickness; $(1-S_w)$ indicates the relative amount of radiation which emerges without being scattered by the wall. This factor is applied to the directional responses for the non-wall-scattered radiation, G_a, and G_d, in Step 8.

6c Position Variations

Elementary calculations assume that the detector is located at the center of a structure. The protection factor, however, can vary from point to point within the structure and it is very useful to be able to calculate the protection factor for detectors located away from the center of the structure.

A convenient procedure to follow in calculating protection factors at various positions is illustrated in Example 5. The basic idea of this procedure is to calculate the contribution from each of the four quadrants which are outlined in Example 5. The calculation for quadrant 1 assumes that the detector is at the center of a fictitious structure just four times the size of quadrant 1; the final result of this calculation is divided by four. This routine is followed in quadrants 2,3, and 4 for both the roof and ground contribution. Since in each case, the contribution for any given structure is divided by four, it is simpler to add up the total contribution for all four fictitious structures and divide the sum by four. (Steps 5,6, and 8). Notice that in Step 6 the calculation for the wall-scattered geometry factor is multiplied by 2. This is because the detector is assumed to be at mid-height and therefore, the upper solid angle fraction equals the lower solid angle fraction. Thus, the radiation scattered in from below the detector plane needs only to be multiplied by two to also account for the radiation scattered from above the plane.

The type of calculation just outlined probably gives reasonably accurate results until the detector closely approaches a wall or corner. When the detector is next to a wall or in the corner of a structure, it is far simpler, and probably just as accurate, to use the short cut calculations described as follows:

a. For a detector located at the wall of an aboveground structure along one of its medial lines: consider a fictitious structure twice as large in area and compute the usual calculations for ground and roof contribution. Then take one-half of this ground contribution and add to it one-half of the barrier reduction factor for the wall case; i.e. $C_g = 1/2\ B_w\ G_g' + 1/2\ B_w$, where G_g' is the geometry reduction factor for ground contribution assuming a fictitious building. The equation for the roof contribution is $C_o = 1/2\ C_o'$, where C_o' is the roof contribution for the fictitious structure.

b. For a detector located in the corner of an aboveground structure; consider a fictitious structure four times as large and then make calculations similar to (a) above. But in this case, take one-fourth of the ground contribution for the fictitious building and add three-fourths of the barrier reduction factor for the wall case, i.e. $C_g = 1/4\ B_w\ G_g'' + 3/4\ B_w$* where G_g'' is the geometry reduction factor for ground contribution assuming a fictitious building. Similarly, the roof contribution is one-fourth of the total roof contribution for the fictitious building, i.e. $C_o = 1/4\ C_o''$.

6d <u>Basement Shelter</u>

The radiation from fallout arriving at a detector in a basement with unexposed foundation walls must take one of four paths:

1. It can come from roof sources and pass through the intervening roof and floor slabs before arriving at the detector.

2. It can come from ground sources and arrive at the detector after it is scattered by the ground floor wall and has penetrated the ground floor slab.

3. It can come from ground sources, be scattered by the air, and then in order to arrive at the detector, it must penetrate the ground floor slabs; this is the skyshine contribution.

4. It can come from ground sources and arrive at the detector after penetrating the surrounding earth and foundation walls.

In Example 6a, it is seen that contribution to the dose at the detector from roof sources is extremely small since the total overhead mass thickness, X_o, is 330 psf (Step 7). Further,

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*When walls are very thick (X_w is much greater than 40 psf), $1B_w$ should be used in lieu of $3/4\ B_w$.

the contribution through the earth and foundation walls is assumed to be negligible. This leaves the contributions from wall-scattered radiation and skyshine to be considered by differencing techniques. The geometry reduction factor for wall-scattered radiation is calculated in Step 3. Similarly, the geometry reduction factor for skyshine is calculated in Step 4. The total ground geometry reduction factor, G_g, is the sum of these two contributions as given in Step 5. Next, it is necessary to take into account the barrier reduction factors for both the wall, B_w, and the overhead roof slab, B_o'. In Step 6, the reduction factor for the combined barrier and geometry effects is calculated. Finally, the total reduction factor for both the roof and ground contribution is obtained and its reciprocal, the protection factor is calculated.

Even a small exposure of the basement wall abovegrade can have rather pronounced effects on the protection factor of a basement shelter. Often, the bulk of the contribution to the dose at the detector is that which comes from ground sources and reaches the detector after being scattered by the exposed portions of the basement wall. The calculation for this contribution is very similar to that just described in Example 6a; the main difference is that there is no barrier reduction factor for the overhead floor slab. In Example 6b, it is important to note that the contribution through the basement wall must be added to the contribution from the first floor wall as shown in Step 7. Attention should also be given to the fact that a 2-foot exposure in this basement with a 10-foot ceiling height, is responsible for the protection factor being decreased by over a factor of 10 (1750 vs. 165).

If there is danger of the fallout particles piling up on any of the exposed basement walls, then the protection factor would probably be further decreased. The effect of pile-up, however, is a special shielding problem and is covered in Sec. 9b.

6e Upper-Story Shelter

A shielding analysis for an upper-story shelter is illustrated in Example 7. The first three steps are the usual preliminary calculations to determine the appropriate solid angle fractions. The reason that the solid angle fraction for the roof, ω_o, is not calculated will be discussed later.

In Step 4, the ground contribution through the 5th floor wall is computed. The calculations are very similar to those presented in Example 4. The main difference is the necessity to take into account the height of the detector above the contamination. In the directional response for direct radiation, G_d, (Step 4b); the height is important since much of the direct radiation is assumed to be "shadowed out" by the floor slab of the 5th floor (Fig. 17a). Height is also an important parameter in determining the wall barrier reduction factor (Step 4d).

The calculations for the ground contribution through the 6th floor wall, which are described in Step 5, are very similar to those of Example 6a. Again, the main difference is the necessity to take height into account. In Step 5d, the wall barrier reduction factor is a function of the wall mass thickness and the height measured from the contaminated plane to the mid-point of the 6th floor wall, 55 feet.

The calculations in Step 6 for ground contribution through the 4th floor wall must take into account a differential "shadow effect" which is illustrated in Fig. 17b. In Step 6d, the wall barrier reduction factor must be obtained by using the height of the mid-point of the 4th story, 35 feet. Also, in this step, it will be noted that the shielding effects of the floor slab below the detector (that is the 5th story floor slab) are accounted for by using the barrier curve for Case 1.

Since the total overhead mass thickness is very large, it can be assumed that the geometry effects associated with the roof contribution are not significant and therefore the barrier reduction factor, $B_o\ (X_o)$ is assumed to be equal to the reduction factor for combined shielding effects, $C_o\ (\omega_o, X_o)$. Thus, the roof contribution, Step 7b, is found from Chart 1, without having to obtain the solid angle fraction, ω_o. Note also that barrier reduction factors for separate overhead barriers should not be multiplied but instead the sum of the mass thicknesses of the separate barriers should be obtained and a single barrier reduction factor based upon this total overhead mass thickness should be used, or symbolically:

$$\text{Use } B_o\ (X_1 + X_2 + \ldots . X_n)$$

$$\text{Do not use } B_o\ (X_1) \times B_o\ (X_2) \ldots . . B_o\ (X_n)$$

In Example 7, it is interesting to note the relative contributions to the detector. For example, the contribution through the 5th floor walls accounts for about 93% of the dose; the contribution through the 4th floor walls accounts for about 6% while the contribution through both the 6th floor walls and roof account for less than 1% of the total dose. This, of course, indicates that increasing the mass thickness of the 5th floor wall would be the most effective means for increasing the protection factor of this particular shelter.

In summary, the aboveground shelter problem illustrated in Example 7, is the most general case of the simple shelter situations. The over-all approach has been to break the ground contribution into three separate calculations. First, to consider the radiation

penetrating the walls adjacent to the detector, that is on the same floor; second, to consider the radiation which passes through the wall on the story above the detector; third, to consider the radiation which penetrates the wall on the story below the detector. Of course, these same calculations could be continued for more stories above or below the detector, as required. Usually, however, it is only necessary to consider the stories immediately above and below the detector. Finally, the total ground contribution must be added to the roof contribution in order to determine the total reduction factor.

CHAPTER VII

APERTURES

7a Windows

It is often necessary to take into account the effect of windows in wall barriers. A detector immediately behind a window is subject to both direct radiation from the ground and the skyshine. In Fig. 18a, it is seen that the effect of moving the detector away from the window is principally to decrease the angular size of the zones through which the direct and skyshine radiation can pass. Since windows are assumed to have little or no mass thickness, barrier effects are of no consequence.

If a detector is moved from the center of a window to near the top of the window, it can be seen that the zone through which direct radiation is received from the ground is now increased whereas the skyshine zone is virtually eliminated. Since, for any given solid angle fraction the directional response for radiation from ground sources, G_d, can be many times more than that of skyshine source, G_a, a detector near the top of the window will generally have a far higher reading than a detector at window midheight (as shown in Fig. 18).

Conversely, a detector at sill level will be subject to only the skyshine which passes through the window and therefore a protection factor at this point would be greater than either of the other two detector positions (Fig. 18b).

For convenience of calculating, it is often assumed that a detector is located at sill level. This assumption is justified by the fact that the protection factor at a detector much above sill level is so low when compared to the protection factor at or below sill level that it is common practice to have any designated shelter area below sill level. (N. B. Even sill heights of 3 feet or so would permit shelter occupants to sit on the floor and still be below sill level.)

In Example 8, the calculations for ground contribution through windows in a barrier wall are illustrated. Note that the assumption of the detector plane at sill level necessitates the computation of only one solid angle (ω_a). There are several other important points illustrated in this calculation. First of all, the starting point of this calculation is the ground contribution through the wall assuming it has no windows (Step 1b). Next, it is necessary to find out how much of this total contribution through the solid wall came from that portion of wall which is actually occupied by the windows.* This

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*Notice that the relative amount of windows is described by P_a, the perimeter ratio of apertures, and not by A_p, the percent of apertures which is based on wall areas. Sec. 8a, Sector Analysis.

computation is shown in Step 1c. By subtracting Step 1c from Step 1b, the ground contribution through the actual solid portion of the wall is obtained. It is necessary to add to this, the skyshine contribution through the window itself which is calculated in Step 1d.

In summary, it is first necessary to determine the ground contribution through the wall assuming it has no windows and to subtract from it the ground contribution through that portion of the wall which is actually occupied by the windows but, for the moment, is assumed to be solid. This subtraction yields the ground contribution through that portion of the wall not occupied by windows; then to this is added the actual skyshine contribution through the windows themselves.

To take into account the effect of windows on floors above and below the story on which the detector is located, a simple device is used. This is to calculate the ground contribution through the wall as if it were 100% solid and also calculate it as if it were with 100% windows. Then to proportion the contribution by the percent of wall area actually occupied by windows. Step 2b is the calculation assuming the wall consists entirely of windows (A_p = 100%). Notice it is merely the differencing of two directional responses for skyshine multiplied by two barrier factors. The first barrier factor is for the wall and assumes a wall mass thickness of zero psf and a height of 55 feet, which is the mid-height of a 6th story wall. The second barrier factor is, of course, B_o' which takes into account the floor slab of the 6th story.

The adjusted ground contribution through the 6th floor wall which takes into account the windows is shown in Step 2d where (a) the ground contribution assuming no windows multiplied by .8 (80% of the wall is solid) is added to (b) the ground contribution assuming only windows multiplied by .2 (20% of the wall is occupied by windows).

In Step 3, the calculation is very similar to those just described in Step 2. The main difference being that the differenced directional response for direct radiation, G_d, is used instead of the skyshine radiation, G_a.

7b Passageways

A horizontal passageway may be associated with a ground floor entrance to a shelter area. Present practice would have the passageway walls of about the same mass thickness as the exterior walls. If this is done, then a detector in the passageway would receive radiation which comes principally down the passageway itself. For this special case, a directional response, A_v, has been developed and it is graphically shown as Case 2, Chart 10. The use of this curve is illustrated in Example 9a, which is a straight forward calculation. First, it is necessary to calculate the solid angle fraction subtended

at the detector by the entranceway opening. (N. B. For convenience, the detector is assumed to be located on a perpendicular from the mid-point of the door.) Using this solid angle fraction, the appropriate directional response, A_v, is found. (Step 3).

For subsequent changes of direction, it is necessary to use solid angle fractions directly as multipliers since the directional response in this case is not well defined. But experimental results indicate that the solid angle fraction subtended by a detector in the second leg of an L shaped corridor should be reduced by a factor of .1 to account for the diffusion of the radiation as it scatters around the first right angle turn. (Step 4). In subsequent 90^{o} turns in the passageway the solid angle fraction should be reduced by a factor of .5.

Note that the above calculations refer to the contribution to the detector through the entranceway alone and must be added to the ground and roof contribution in order to find the total reduction factor at the detector itself. Note also that these calculations assume the mass thickness of the entrance door to be close to zero.

7c Shafts

Sometimes shelter entranceways are vertical shafts or shelter areas are otherwise associated with shafts. It is therefore necessary to develop directional responses for two special cases. For the directional response, A_h, it is assumed that the shaft is covered with a weightless material on which the fallout particles are uniformly distributed, and there is no skyshine contribution into the shaft. The second case, A_a, assumes that there are no fallout particles above the shaft and only skyshine is considered.

The application of these directional responses to a particular problem is illustrated in Example 9b. It is merely a question of computing the solid angle fraction subtended at a centrally located detector under the shaft opening and adding the directional responses for the direct radiation, A_h, to the directional response to the skyshine, A_a, in order to find the reduction factor at the detector. (Step 2). If it could be assumed that the fallout particles would not remain on the shaft cover, then, of course, only the skyshine directional response need be considered. For corridors or passageways leading from a vertical shaft the technique described in Example 9a is used.

In Step 4, for example, we see the solid angle fraction of ω_2 is multiplied by a factor of .1 to gain an estimate of the reduction factor between detector b and c.

CHAPTER VIII

COMPARTMENTALIZED STRUCTURES

8a Sector Analyses

The basic approach to the problem of shielding analyses is to consider a simple structure with only one type of wall construction. Often, however, different portions of a building have different types of construction. For example, the walls on the street side of a building may have 20% to 50% windows, whereas the wall on an alley side might have little or no fenestration. Also, the internal arrangement of interior partitions is more often than not unsymmetrical, so that radiation coming from one direction may have to pass through several wall barriers, whereas in another direction it may only have to pass through a single wall barrier. It is necessary, therefore, to be able to analyze a structure to take into account variations of this type. For a simplified calculation* the perimeter ratio technique is used. However, a more detailed analysis requires the use of the azimuthal sector.

The azimuthal sector approach is illustrated by Fig. 19a. In this figure is shown, the plan view of a building with 4 different wall constructions and the azimuthal sectors subtended by the detector for each different wall. To calculate the ground contribution to the wall type in sector 1, Az (1), it is necessary to assume a fictitious building in which all 4 walls are of this type and which has dimensions as shown in Fig. 19b. The calculations for ground contribution for this fictitious building are completed in the usual manner and then adjusted by the azimuthal fraction which a wall occupies in an actual structure. In other words, the contribution through the wall subtended at the detector in azimuthal sector Az (1) equals Az (1) x C_g' where Az is the azimuthal angle of the sector in degrees divided by 360° and C_g', is the ground contribution assuming the fictitious building.**

If the azimuthal sector is very small then the detector can be considered at the center of a large fictitious cylindrical structure. (Fig. 20). The calculations for the solid angle fraction are then simplified and the equation given in Fig. 14a can be used. For example, if the detector is to be considered 3 feet above the floor and the distance from the wall segment to the detector is D. then tan θ = D ; then ω_1 = 1-cos θ. This solid angle fraction must, in turn, be multiplied by the appropriate azimuthal sector.

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*See "Fallout Shelter Surveys: Guide for Architects and Engineers" NP-10-2, Office of Civil and Defense Mobilization, Washington 25, D. C. 1960.

**Note that the azimuthal sector, Az, is expressed as a decimal and <u>not</u> in degrees, i.e. $Az = \frac{\text{azimuthal angle}}{360}$

Sometimes, however, azimuthal sectors are used in lieu of, P_a, perimeter ratio of apertures, in shielding analysis for windows. This would probably not be necessary, unless the windows are irregularly spaced or few in number. (Fig. 20).

In general, analyses by azimuthal sectors should not be used to account for off-center detector positions. Procedures for varying the detector position in a given shelter area are presented in Sec. 6c.

8b <u>Parallel Partitions</u>

Up to this point, shielding calculations have been confined to simple structures, that is rectangular structures which have no interior partitions. Most structures, however, have interior partitions which must be taken into account since they may greatly influence the protection factor. Thin interior partitions such as stud walls with gypsum wallboard; semi-permanent sheet metal partitions and the like usually do not significantly influence the protection factor and consequently are often excluded from shielding calculations. On the other hand, brick, block or other masonry walls of 4 inches or greater thickness can noticeably increase protection factors.

The simplest situation involving interior partitions is called the parallel partition case and is illustrated in Fig. 21. Each interior partition is parallel to a corresponding exterior partition. This type of partition influences the shielding analysis in two ways. First of all, radiation from sources on the roof which are located on the peripheral areas outside of the central core (the shaded area in Fig. 21) must, in addition to the roof slab, also pass through the interior partition in order to reach the detector.

Secondly, the radiation from ground sources which pass through the exterior wall must also now pass through the interior partition in order to reach the detector.

In Example 10, the procedure for taking into account ground contribution passing through interior partitions is shown in Step 2. It merely requires the calculation of the structure assuming no interior partitions and then multiplying this ground contribution by a barrier factor which is a function of the mass thickness of the interior wall. Note that the barrier factor for interior partitions in this case is taken from Case 2, Chart 1, since the additional correction for height is already included in the barrier factor for the exterior wall.

It is quite obvious that the contribution from the roof area within the core area defined by the interior partitions can be calculated directly from Chart 4 (Step 3a). To calculate the roof contribution from the peripheral root area which must also pass through the interior wall, it is first necessary to make a calculation assuming the wall does not exist. This means that the contribution based upon the core roof area, C_o (ω_o', X_o) must be subtracted from the contribution from the total roof area, C_o (ω_o,X_o). This is done in Step 3b which gives the roof contribution from the peripheral areas, if no interior partitions existed.

To account for the interior wall barrier factor the mass thickness of the peripheral roof slab is converted to an equivalent height of air. In this case, a particular radiation path from a peripheral roof source would have to travel through .53 feet of concrete (80 psf/150 pcf; or 1,040 feet of air (80 psf/.077 pcf)* before striking the interior partition. Using this equivalent distance in air (also termed fictitious height, H_f) the ratio of reduction that would occur with a barrier of mass thickness equal to that of the partition, and a barrier with 0 mass thickness, can be determined using Chart 2 (Step 5). The contribution from the peripheral area (step 3b) which assumed no interior walls, is then multiplied by this ratio from Step 5. The product is the combined reduction factor for radiation which has passed through both the roof slab and the interior wall before arriving at the detector.

When windows are involved, parallel interior walls can be particularly important for shelters. The method of taking the barrier effects of these interior partitions into account is similar to that described in Example 10. Ground contributions are calculated as if there are no interior partitions as in Example 8, and then the barrier reduction factor for the interior partitions, B_w (X_i, 3') is found from Case 2, Chart 1. The product of the ground contribution from Example 8 and the barrier reduction factor is the new reduction factor which takes into account the interior partitions. Example 11 illustrates this calculation.

8c <u>Perpendicular Partitions</u>

Often, partitions which are perpendicular to exterior walls are used to subdivide a structure into different rooms. When these partitions have any substantial mass thickness, they can increase the protection factor of a given shelter area. In Fig. 22a, which is a sketch plan of a structure that has both parallel and perpendicular partitions, one of the azimuthal sectors which is influenced by a parallel partition and two azimuthal sectors which are influenced by both parallel and perpendicular partitions are shown.

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* or H_f = $13X_o$

The present method for taking into account the perpendicular partitions is illustrated in Fig. 22b. Here it is shown that for the azimuthal sectors, which are influenced by the perpendicular partitions, the mass thickness of the perpendicular partition is added to that of the parallel interior partition and the calculation for that sector is completed with the methods described in Sec. 8b. If there were two perpendicular partitions in any given azimuthal sector then the mass thickness used in the calculation would be the sum of the two intervening perpendicular partitions and the parallel interior partitions. This method of calculation would be used whether or not the exterior wall had windows.

CHAPTER IX

SPECIAL SHIELDING PROBLEMS

9a Effects of Terrain and Ground Roughness

Shielding calculations are generally for a structure which is located in a uniformly contaminated, smooth infinite plane. It is necessary to modify these calculations to account for the effects of terrain and ground roughness.

Terrain effects are variations in reduction factors caused by nearby artificial or natural features which limit the field of contamination, i.e. deviations from an infinite plane. Artificial features may be buildings, masonry property walls, embankments and the like. Examples of natural features are lakes, rivers, ravines, cliffs, etc.

Ground roughness effects are variations in reduction factors caused by relatively small crenulations in the surrounding terrain, i.e. deviations from an ideally smooth plane. Examples of ground roughness include deeply plowed fields, paved areas, turfed areas, etc. Unfortunately, little experimental shielding information is available on the effects of either terrain or ground roughness. However, by coupling available experimental information with theory, a judgment can be given as to how much terrain and ground roughness influence the protection afforded by a specific structure.

An adjacent structure, such as a building, limits the width of the contamination on one side of a shelter; the amount of radiation incident on this shelter wall is reduced and the protection factor is increased. Unfortunately, the interrelationship of detector height directional response and wall barrier factors with width of contamination is very complex. Making some simplified assumptions and treating non-wall-scattered and wall-scattered radiation components separately, a calculation can be made which accounts for a mutual shielding effect of an adjacent structure.

The structure shown in Example 12 has one wall mutually shielded and presents one method of treatment of such a situation.

The solid angle fractions which must be determined for the non-wall-scattered directional responses are computed using the horizontal dimensions employed for the mutually shielded wall for L and W and for Z, the vertical distance between the detector height and the intercept with the exterior wall of the ray drawn from the detector to top or base of the mutual shielding. Directional responses from the mutually shielded azimuthal sector are differenced to find the net response on the assumption that no ground direct or skyshine radiation originates in the solid angle and sector subtended by the vertical wall of the mutual shielding.

Wall-scattered radiation contributed to a detector may originate from the entire field of view seen from the entire field of view seen from the contributing point on the exterior wall. On this basis, the entire wall that faces the mutually shielding is treated the same. The effect of a wall seeing only a strip of contamination of finite width and length instead of an infinite field is provided by use of a reduced barrier reduction factor, B_{ws}, which is then applied in place of B_e to the wall-scattered component found in the usual manner. B_{ws} for a limited field is determined by finding the solid angle fraction, ω_s, of the limited strip as seen from a point on the shielded exterior wall opposite the detector and at mid-wall height of the floor under study (i.e., a different ω_s, is found for the contribution of each floor). This solid angle fraction, determined by the method shown in Example 1c, is used with the wall mass thickness, X_e, to determine the barrier factor, B_{ws}, to be applied to the wall-scattered contributions.

The case of a wall-shielded in part, but also seeing an infinite field (as is the case in Example 12) is treated by determining a weighted barrier reduction factor, B, which is a function of the field seen by the point on the exterior wall opposite the detector B_e for the respective floor, and a B_{ws} computed as though the width and length of a limited strip were defined by the dimensions to and of the mutual shielding. The weighted factor, B, is the sum of the factor for the infinite field, B_e, multiplied by that portion of 180° that the point on the exterior wall sees as an infinite field, and of the factor for the shielded case, B_{ws}, multiplied by that portion of 180° seen by the point that is subtended by the mutual shielding.

~~The usual calculations are made for the wall-scattered component (Step 3), but Chart 9 is used in lieu of Chart 2 for the barrier reduction factor, $B_{ws}(X_e, \omega_s)$. In this case the solid angle fraction, ω_s, which "defines" the limits of the contaminated strip is referred to a point at detector height of the walls exterior centerline. The solid angle fraction, ω_s, is found by assuming its apex is located over the center of an area which has double the width of the contaiminated strip (in this case 2 x 20 = 40'); then halving the resulting solid angle fraction as was done in Example 1b. Note that the ω_s for the short wall (.41) is nearly equal to ω_s for the long wall (.42) that the B_{ws} (X_e, ω_s) is considered to be the same for all four walls and only one calculation for non-wall-scattered radiation is necessary.~~

Limited studies indicate that the effects of ground roughness can be estimated by either assuming the ground contamination is covered by a thin barrier of appropriate thickness; or by assuming that the wall penetration curves (Chart 2) can be entered using a

fictitious height which is related to ground roughness. In this manual, the method of using fictitious heights has been adopted for convenience.

Table 6 gives an idea of the fictitious heights which can be added to the actual detector height to account for various degrees of ground roughness. For example, if the aboveground shelter illustrated in Example 4 were located in a plowed field instead of a smooth plane, the fictitious height for this ground roughness would be about (40 ft + 3 ft) or 43 ft; then Chart 2 for barrier shielding effects would be entered assuming this fictitious height instead of the height of 3 ft which was assumed in Step 9 of Example 4. In this case, the total ground contribution, C_g, would equal (.39 x .055) or .021 instead of (.39 x .095) or .037; and the protection factor would be increased from 14 to 18.

In this particular example, the ground contribution is .014 instead of .038 which was determined in Example 4 and the protection factor is increased from 14 to 30. When there are different widths of contaminated strips around a given shelter, then the appropriate methods of sector analysis (Sec 8a) should be applied.

9b Fallout Particle Pile-up

Particles of fallout which have been deposited on turfed areas do not tend to drift, and can be considered to remain more or less uniformly distributed over the area. Field experiments indicate that depositions on paved areas are not so stable. A building located in a parking lot could be expected to have a "pile-up" of fallout particles on its windward side. To estimate the influence of this pile-up on a protection factor, it is necessary to know its relative source concentration. This concentration can be related to the effective "fetch" of the paved area, that is the distance of the outer edge of the pavement from the wall of the building. For aboveground detector positions, the reduction factor accounting for pile-up along a given wall is as follows:

$$R_f(\text{for sector } A_z = 0.18\, P_s(X_w)\, F_e \, \frac{A_z}{r_e}$$

where P_s (X_w) is the barrier reduction factor for a point isotropic source.

F_e is the effective fetch

A_z is the azimuthal sector (Sec. 8a)

r_e is the effective radius, that is the perpendicular distance from the detector to the center of the given wall.

For a belowground detector the equivalent reduction factor is given by the following:

$$R_f \text{ (for sector Az} = \frac{12\,\omega\,(1-\omega)\,(2-\omega)}{UZ}\,B_w\,(X_w)\,F_e\,A_z$$

The various parameters are shown in Fig. 24 or given above.

Note that corrections for pile-up are usually applied to one (or possibly two) azimuthal sectors and the remaining sectors are generally calculated assuming uniformly distributed contamination. Also, unless the effective fetch is extremely great, account must be taken of the contamination outside the paved areas. (Sec. 9a).

9c Filter Rooms

In small family-size shelters, filters are not essential. However, outside air intakes should be designed to prevent fallout particles from being drawn into the shelter. Using the fall velocity of the silt-size fallout particle (Table 1A) as a guide, it can be seen that the intake velocity of the air should not be much greater than 40 fpm if these fallout particles are not to be deflected into a vertical intake opening to the sky. When more practical designs are used, such as common types of raincaps, this intake velocity can be increased markedly. For design purposes in small shelters, the air intake velocity should not be greater than 1,000 fpm, and the air intake should be located at least 2 ft above ground level.

Larger shelters may require a far greater intake of air, and filters should be incorporated into the ventilating system. For fallout shelter purposes, high quality commercial filters are satisfactory. Special filters should be used when protection from biological and chemical agents is required.

The shielding problem associated with filters (or plenum chambers) is to properly isolate them from the occupied portions of the shelter. Table 7 gives some general guidance as to minimum thicknesses of shielding barriers between filter rooms (or plenum chambers) and occupied areas. Apertures in these barriers must be appropriately baffled.

In Table 7, a protected opening is an air intake with a vertical face which is hooded in such a manner as to force incoming air paths to change their direction at least 90 degrees before reaching the opening (Fig. 25). An unprotected opening does not have this hood. In both the protected and unprotected cases, the intake velocities should be kept below 2000 fpm.

TABLE 6

FICTITIOUS HEIGHTS FOR VARIOUS GROUND ROUGHNESS CONDITIONS

Description	Fictitious Height* (Feet)
Smooth Plane	0
Paved Areas	0 - 5
Lawns	5 - 10
Gravelled Areas	10 - 20
Ordinary Plowed Field	20 - 40
Deeply Plowed Field	40 - 60

*To add to actual detector height for use with wall-barrier curves, Chart 2.

TABLE 7

MASS THICKNESS REQUIREMENTS FOR FILTER ROOMS

Air Intake	Protected Opening	Unprotected Opening
100 cfm	nil	50 psf
300 cfm	nil	100 psf
1,000 cfm	50 psf	150 psf
3,000 cfm	100 psf	200 psf
10,000 cfm	150 psf	250 psf

APPENDIX A

CHARTS FOR SHIELDING CALCULATIONS

Fallout is assumed to be uniformly distributed over exposed surfaces according to their horizontal projections. Fallout on vertical surfaces is generally not considered significant.

Chart 1

The energy spectrum of gamma radiation is assumed to be that from fission products at about one hour after weapon burst. It is assumed that the amount of attenuation by a given barrier depends only on its mass thickness and not on the chemical composition of the barrier material. It is applicable to materials with a Z/A* ratio of about 0.5. The three curves were derived from calculations by the moments method.

Case 1

Calculations are based on the assumption of infinite plane isotropic source and a point detector immersed in an infinite homogeneous medium and separated by a mass thickness X_o.

Case 2

Calculations apply to the penetration of radiation from a semi-infinite plane isotropic source on one side of a vertical wall to a point detector on the other side. The detector is located 3 feet above the level of the source plane.

Case 3

Calculations apply to the attenuation of radiation back-scattered from a plane isotropic source which emits only in the forward direction. The source and detector are assumed to be immersed in an infinite homogeneous medium.

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*Z/A = Atomic Number/Atomic Weight

Chart 2

These curves are an extension of Chart 1, case 2, to heights other than three feet.

Chart 3

These curves give the solid angle fraction subtended at a point detector by a rectangular area. They were calculated from the expression

$$w = \frac{2}{\pi} \tan^{-1} \left(\frac{e}{n\sqrt{n^2 + e^2 + 1}} \right)$$

Chart 4

The roof is replaced by a circular disk subtending the same solid angle as the actual roof. This chart gives the ratio of dose rate at X psf from a finite disk source to that at 0.23 psf (3 feet of air) from an infinite plane source. The barrier is assumed to be uniformly distributed between source and detector. The geometry factor depends on the source geometry and the angular distribution of radiation at the detector. Since the angular distribution is dependent on the barrier thickness, the geometry factor is also dependent on barrier thickness.

Chart 5

The walls are replaced by a circular cylinder with vertical axis. The cylinder is determined by the condition that it subtend the same solid angle at the detector as do the real walls. Since the angular distribution of radiation emerging from the inside of a wall is not well known, the directional response is calculated by an approximate method which considers the "non-wall-scattered" and the "wall-scattered" radiation separately. The term "non-wall-scattered" refers to radiation which passes through the walls without interaction, regardless of whether or not it has scattered in the air outside of the structure. The term "wall-scattered" refers to radiation scattered at least once in the walls of the structure.

(1) The directional response for direct radiation from below the detector plane, G_d, was obtained by cumulative integration over the angular distribution of radiation. The latter was obtained by the moments method.

(2) The directional response for direct radiation from above the detector plane (often called "skyshine"), G_a, was obtained in a similar manner. In addition, however, it includes an estimated contribution from radiation which enters the structure from below and is reflected from the ceiling.

(3) The directional response for scattered radiation, G_s, was obtained from an estimate of the angular distribution of the scattered radiation emerging from a vertical wall. It is further assumed that a detector at midheight of a wall receives an equal amount of scattered radiation from above and below the detector plane.

Chart 6

These curves are an extension of Chart 5, Case (1), G_d (ω, 3'), to heights other than 3 feet. However, since the variation of reduction factor with height is already included in the barrier factor (Chart 2), it is divided out of this factor. If G'_d (ω, H) is the geometry factor for direct radiation at a height H above a clearing of solid angle ω, then G_d is given by

$$\frac{G'_d\ (\omega, H)}{G'_d\ (\omega = 0,\ H)}$$

Chart 7

The weighting factor for direct and scattered radiation was calculated from the ratio of scattered radiation to total radiation emerging from a slab of thickness, X. The calculation was made for perpendicular incidence of Co-60 radiation. Since the direct and scattered geometry factors are often very similar, the net geometry factor is not too sensitive to this weighting factor.

Chart 8

An eccentricity factor is included in the scattered geometry factor to correct for the shape of the building. This factor is based on the assumption that the dose rate from a wall of fixed height and length L at a distance D from the detector is proportional to

$$E = \frac{L}{2}\left[\left(\frac{L}{2}\right)^2 + D^2\right]^{-1/2}$$

Note that for an infinitely long wall (i.e. $L/D \to \infty$) $E \to 1$

For a rectangular structure with contributions from all walls and length, L, and width, W, the factor is $E = \frac{L+W}{(L^2+W^2)^{\frac{1}{2}}}$.

Chart 9

In cases where a finite source surrounds a structure the mutual shielding factor for wall-scattered radiation is used instead of the barrier factor for the infinite source (Chart 2).

The curves of Chart 9 were obtained by calculation of the penetration of radiation from a semicircular source subtending the same solid angle as the actual rectangular strip. All solid angles were calculated relative to a point at detector height on the vertical median line of the wall.

Chart 10

Calculations apply to the response of a detector with a conical collimator of solid angle ω.

Case 1

This calculation applies to the reduction factor in a vertical shaft below a horizontal circular aperture, such as a skylight, which is covered with radioactive material. The value of $R_f = 1$ for $\omega = 1$ corresponds to a detector which is separated from the source by a barrier thickness equivalent to three feet of air (i.e. 0.23 PSF).

Case 2

This calculation applies to the reduction factor in a horizontal passageway leading from a vertical circular aperture. The value of $R_f = 1/2$ for $\omega = 1$ corresponds to a detector which is located in the vertical plane of the aperture and thus receives radiation from a semi-infinite plane.

Case 3

This calculation applies to the reduction factor on a vertical shaft below a horizontal circular aperture which is not covered with radioactive material. The value of $R_f = 0.1$ for $\omega = 1$ corresponds to a detector which is located in the horizontal plane and thus measures the total skyshine contribution.

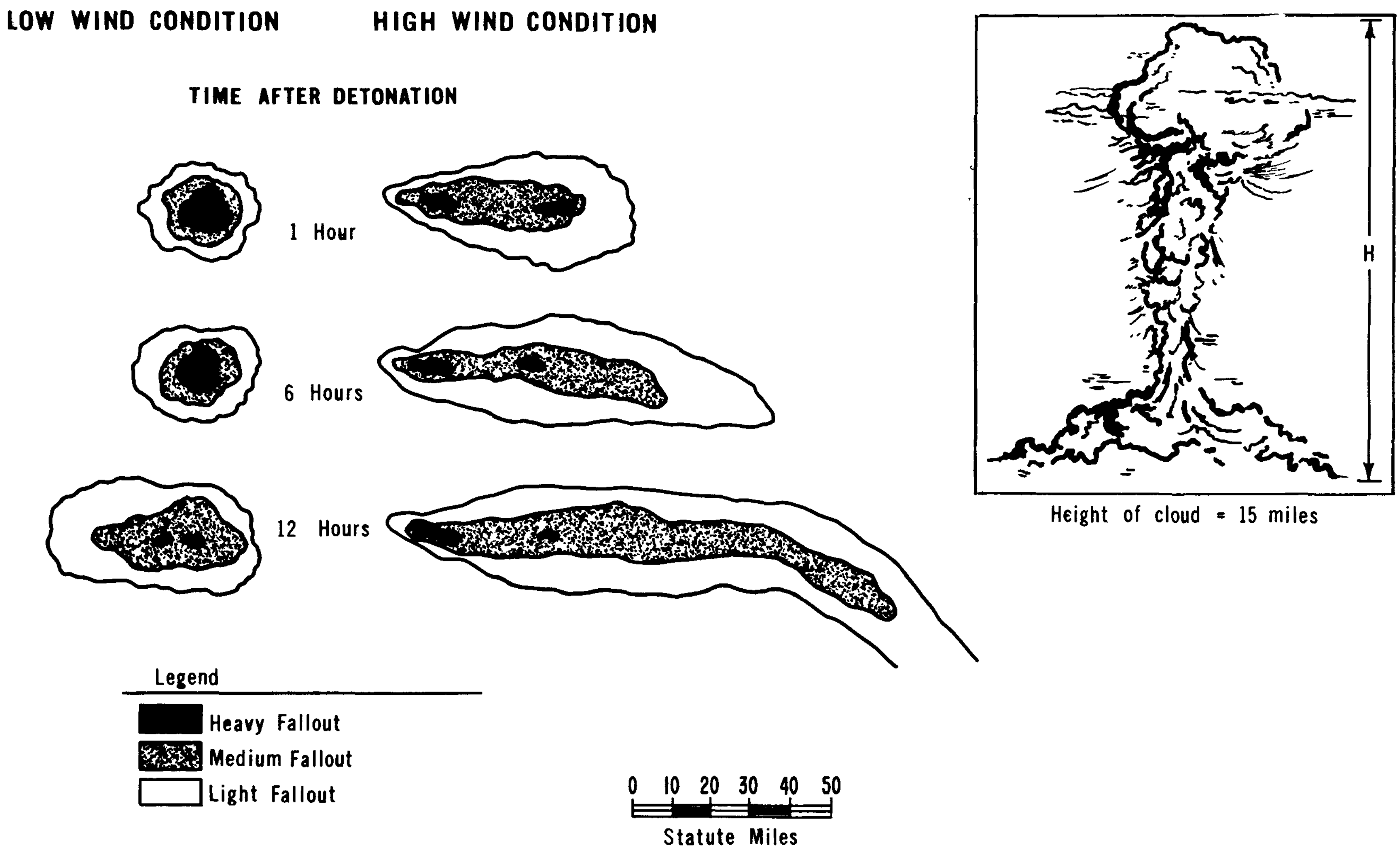


Fig. 1. Idealized Regional Distribution of Fallout from Single Nuclear Weapon in Megaton Range

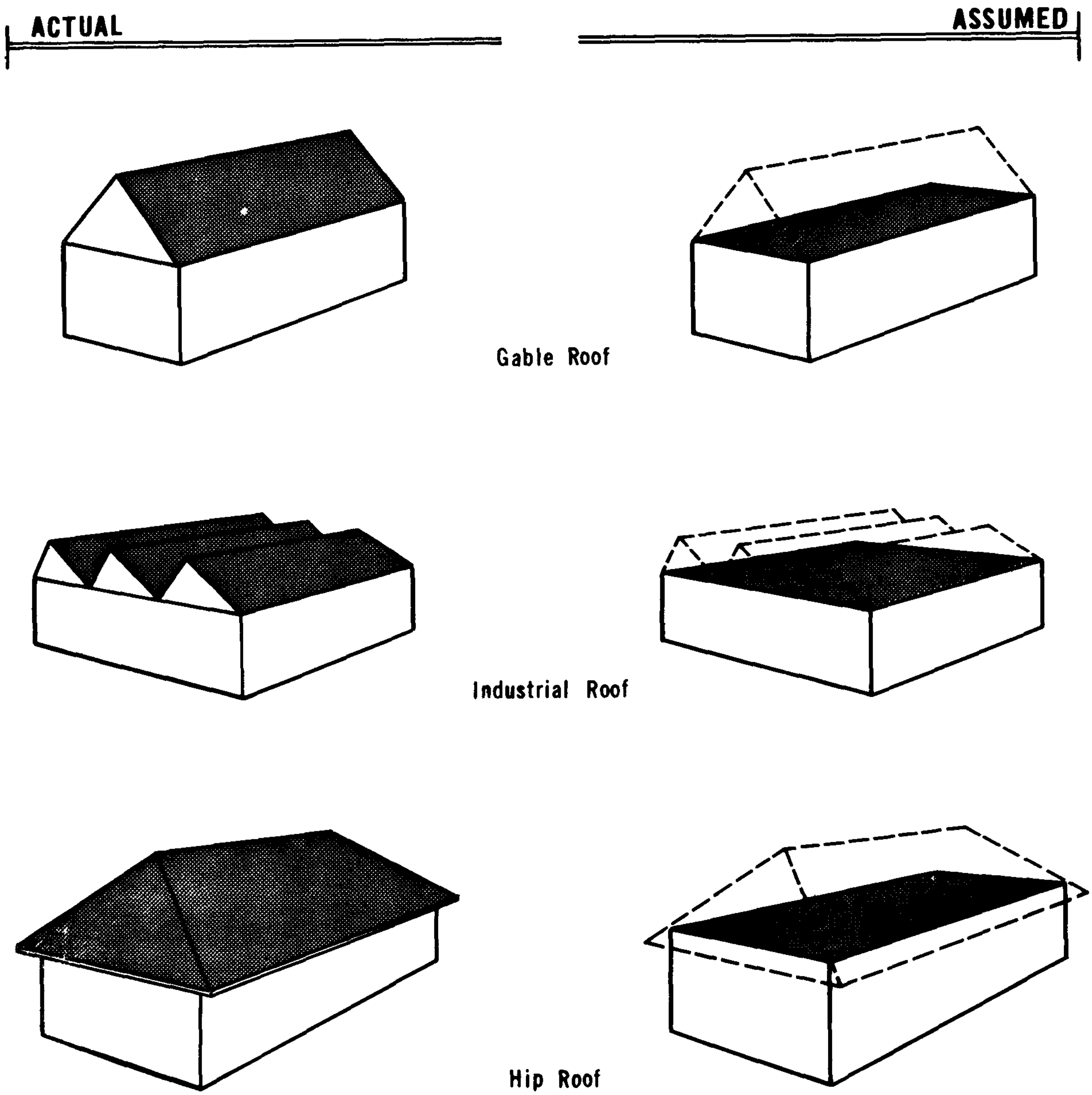


Fig. 2. Idealized Distribution of Fallout on Roofs

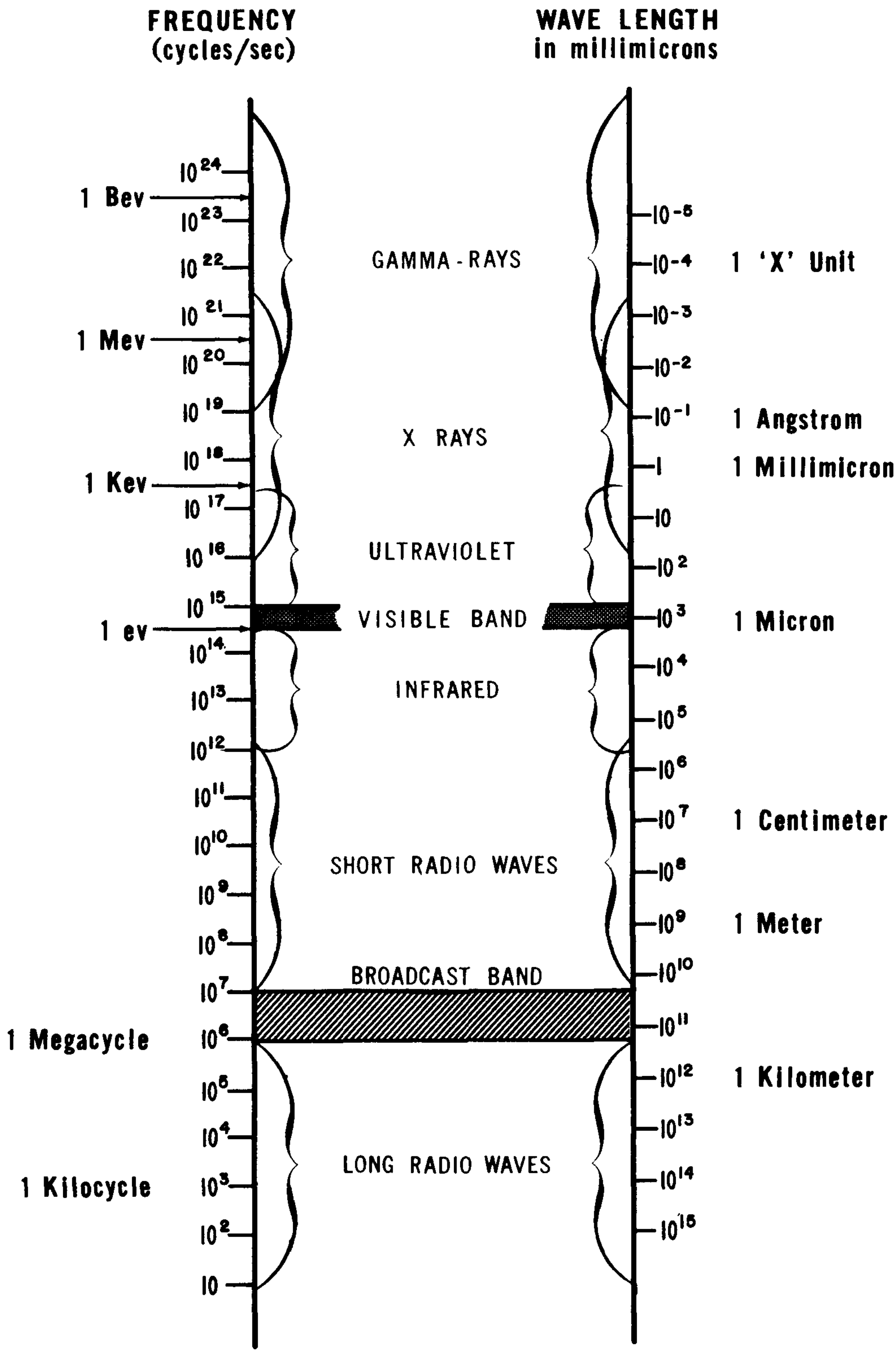


Fig. 3. Electromagnetic Spectrum

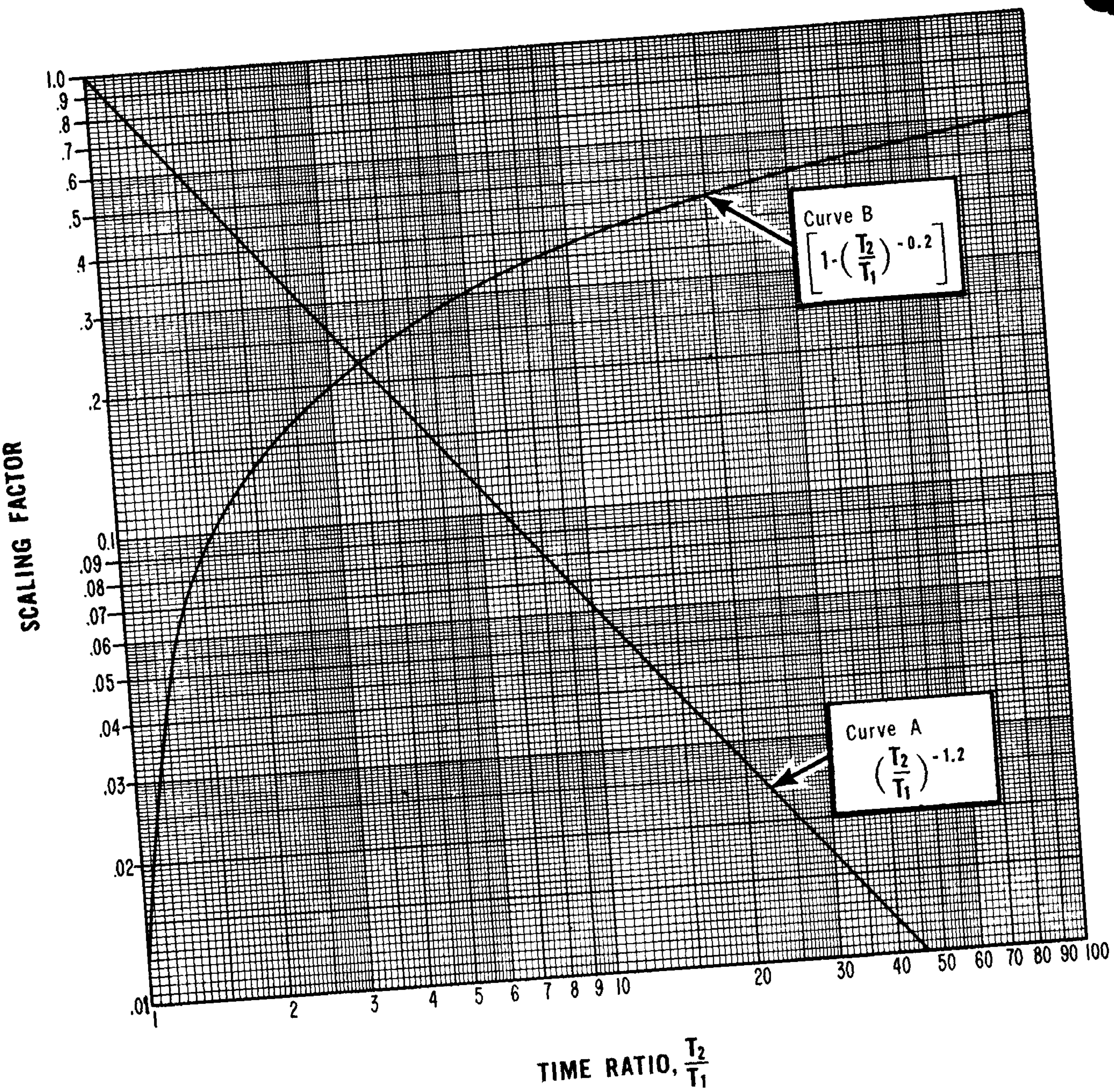


Fig 4. Decay of Fallout Gamma Radiation

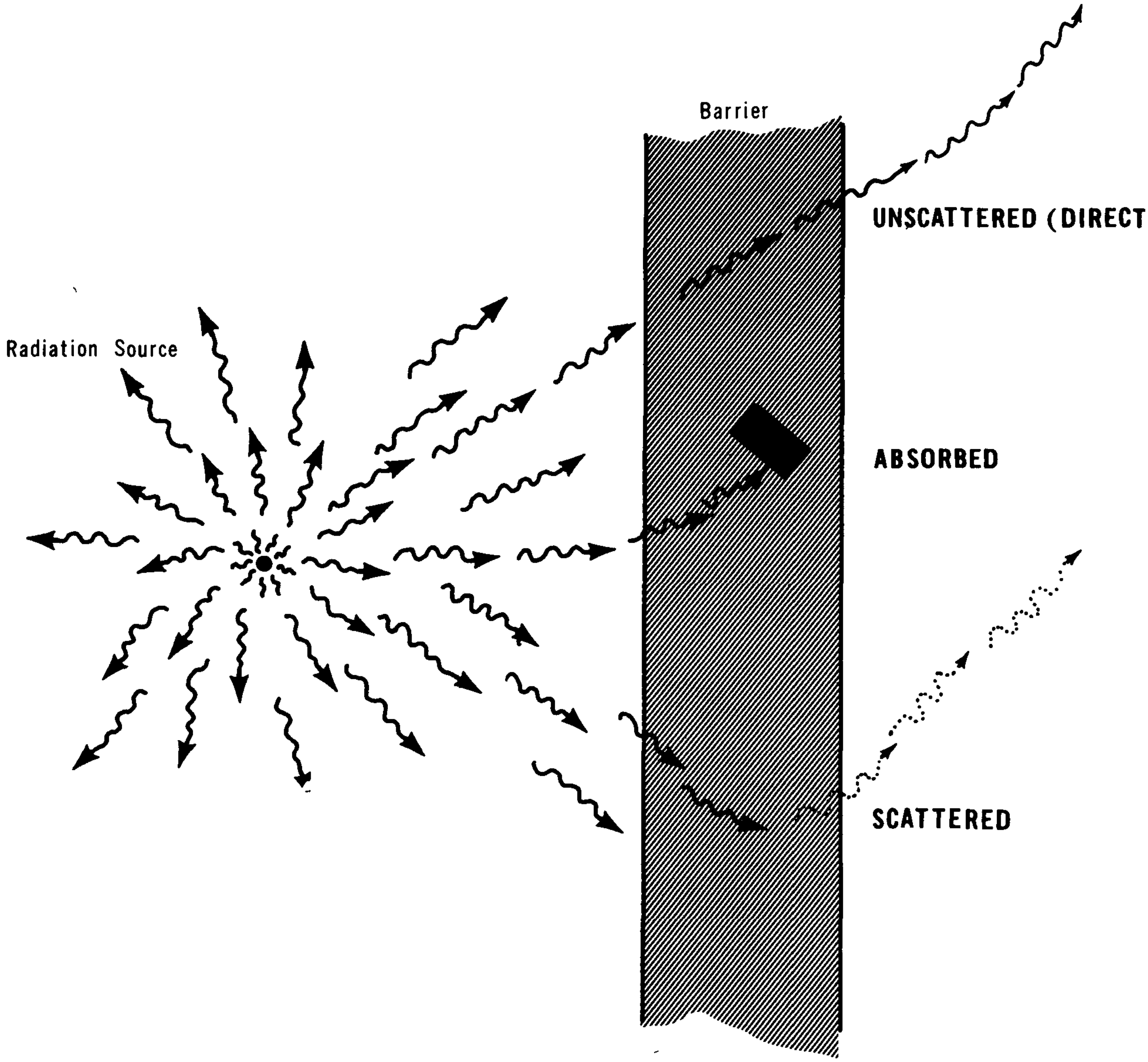


Fig. 5. Gamma Radiation Paths

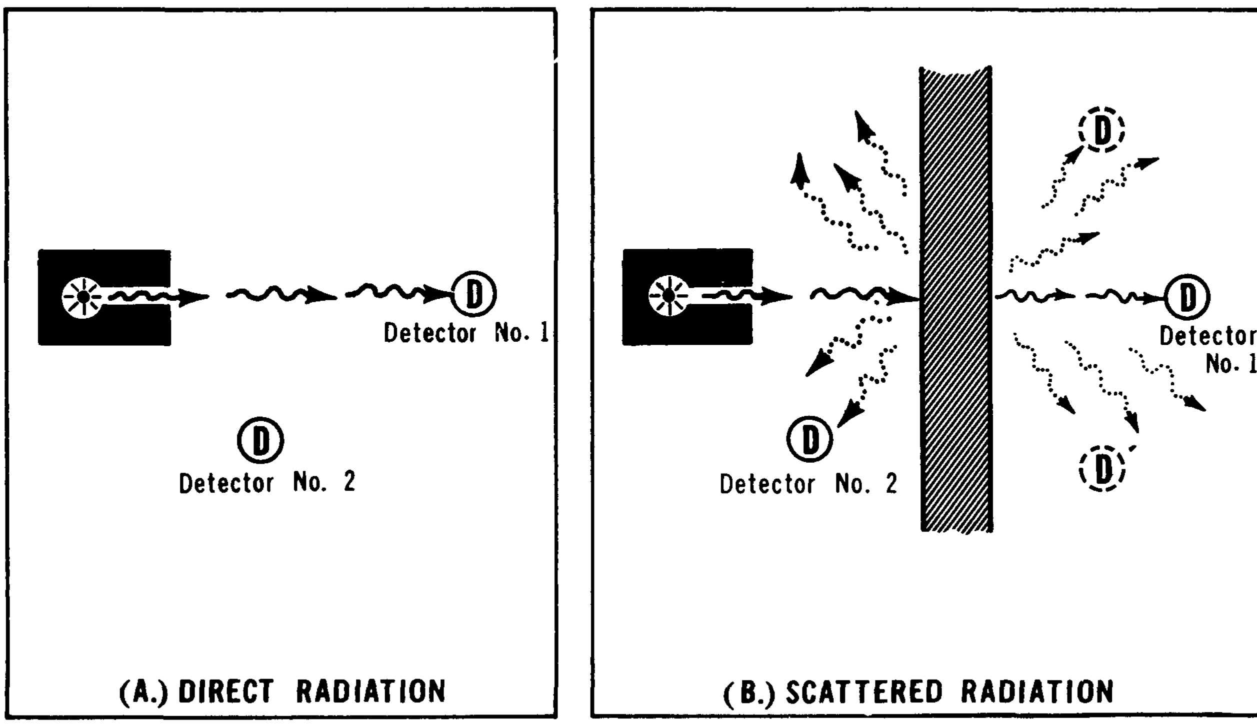


Fig. 6. Scattering in a Barrier

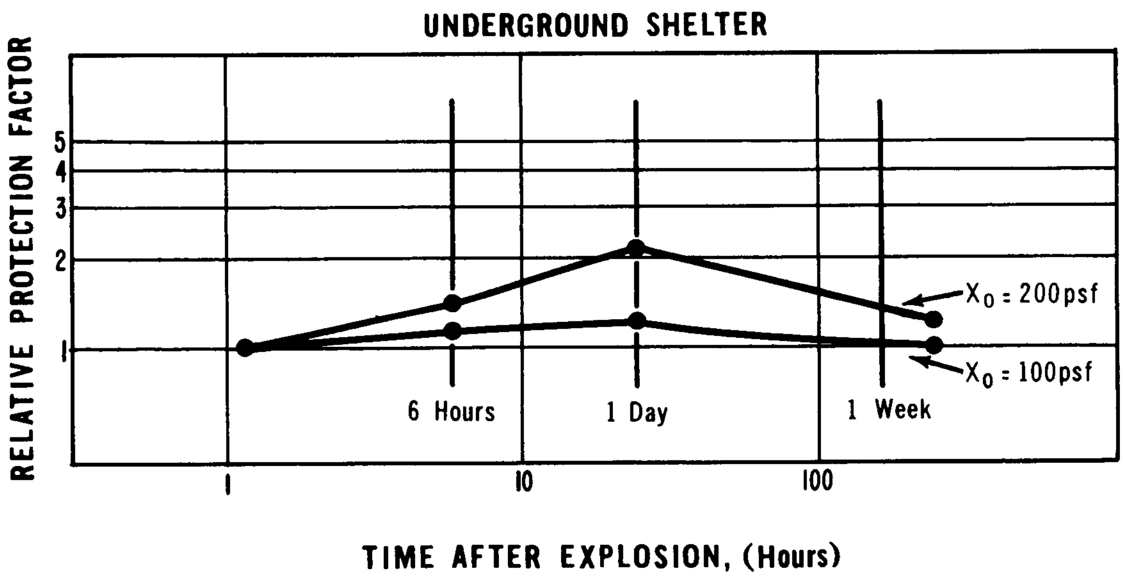
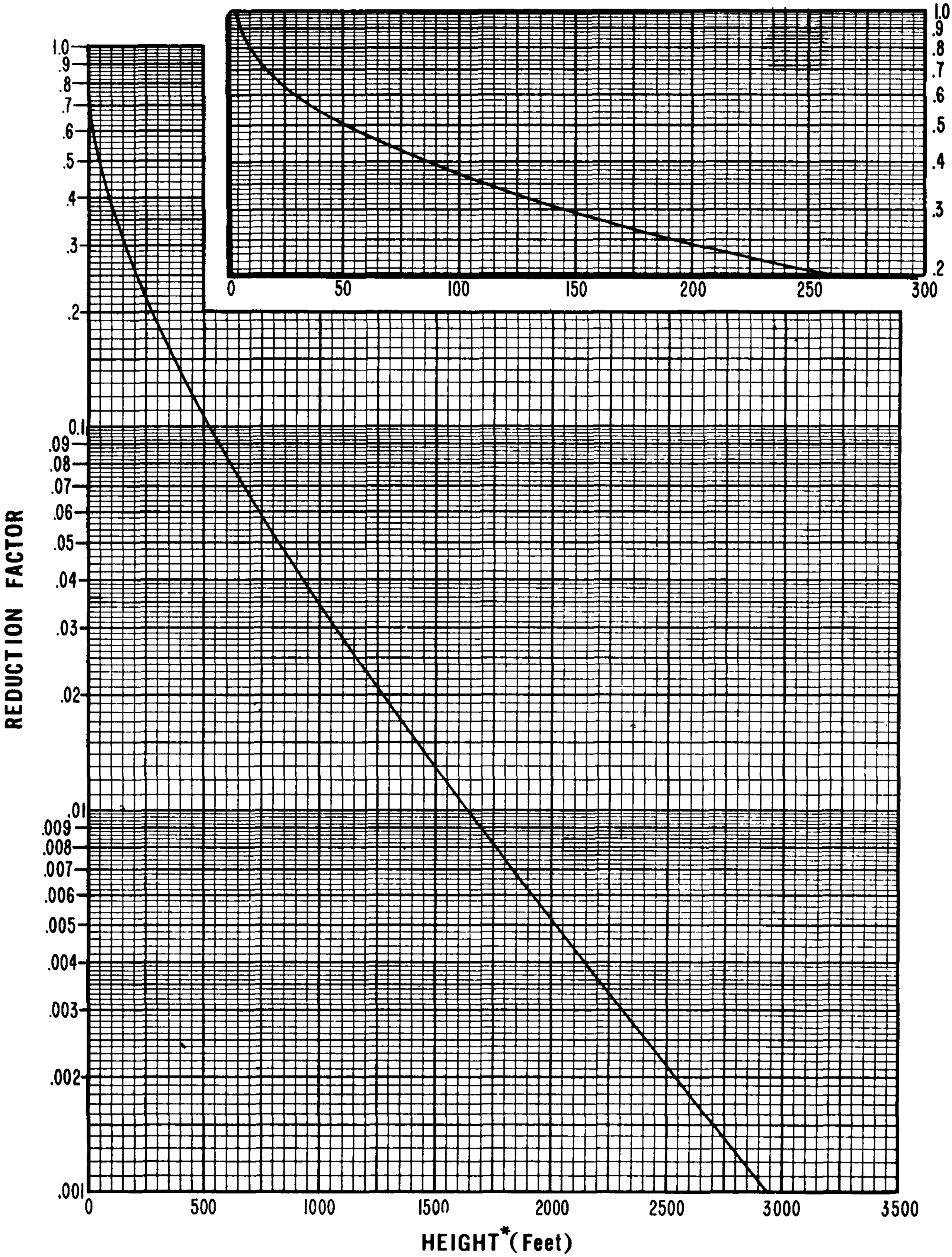
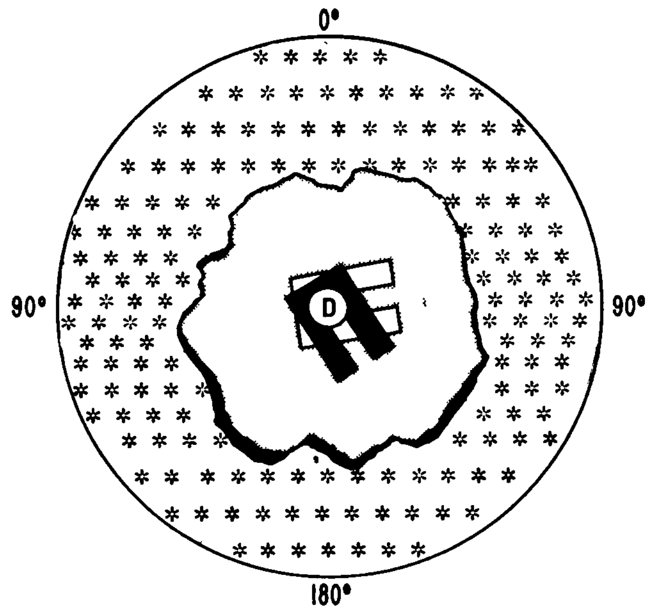


Fig. 7. Variation of Protection Factor with Time

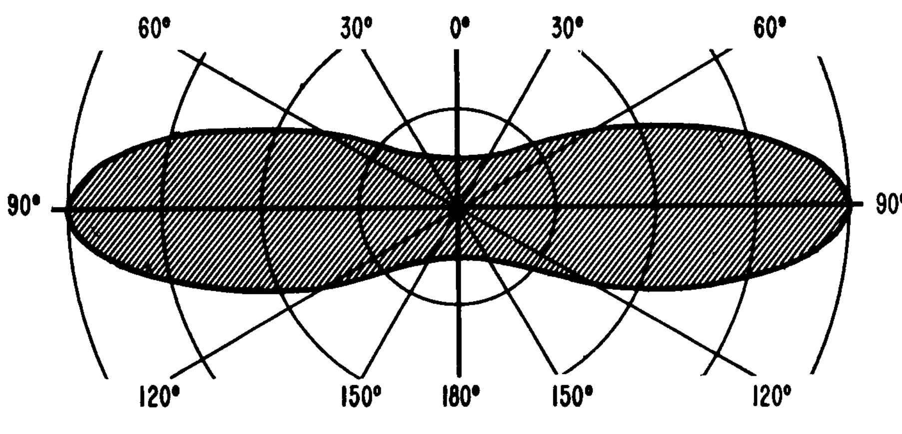


*or slant radius of cleared area in a uniformly contaminated plane of indefinite extent. (skyshine is included)

Fig. 8. Reduction Factors for Height Variations

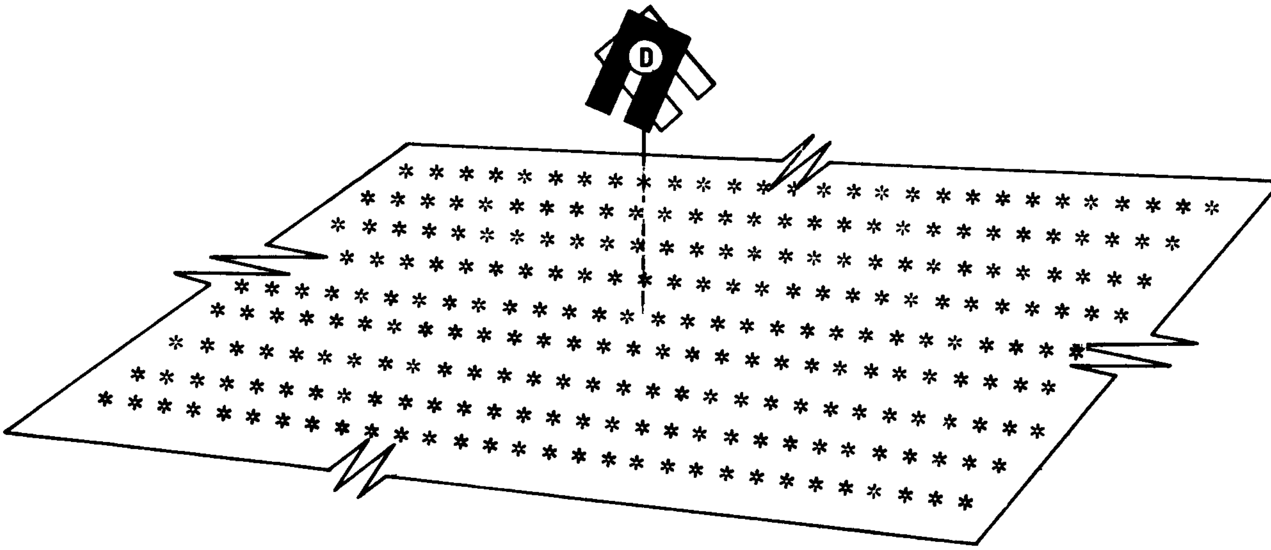


(A.) SPHERICAL CASE

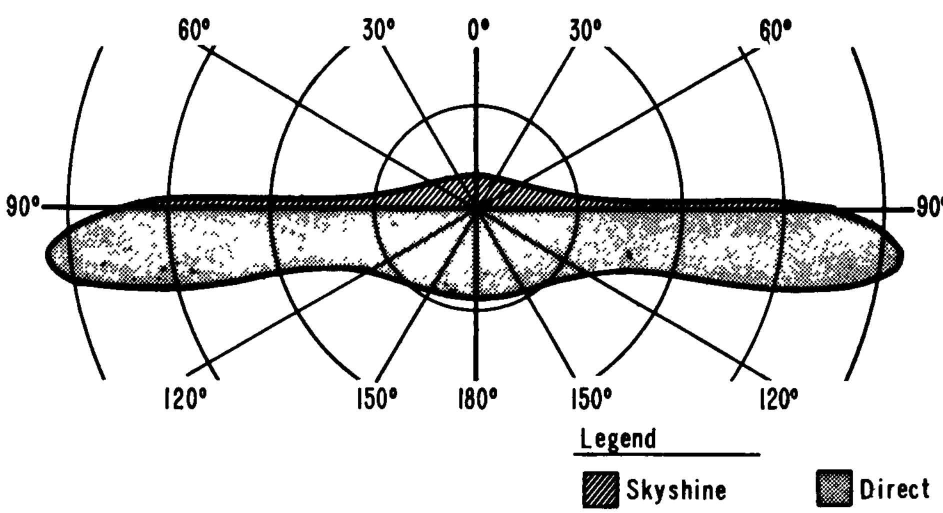


(B.) POLAR DIAGRAM FOR SPHERICAL CASE

Fig. 9. Directional Distribution (Spherical Case)

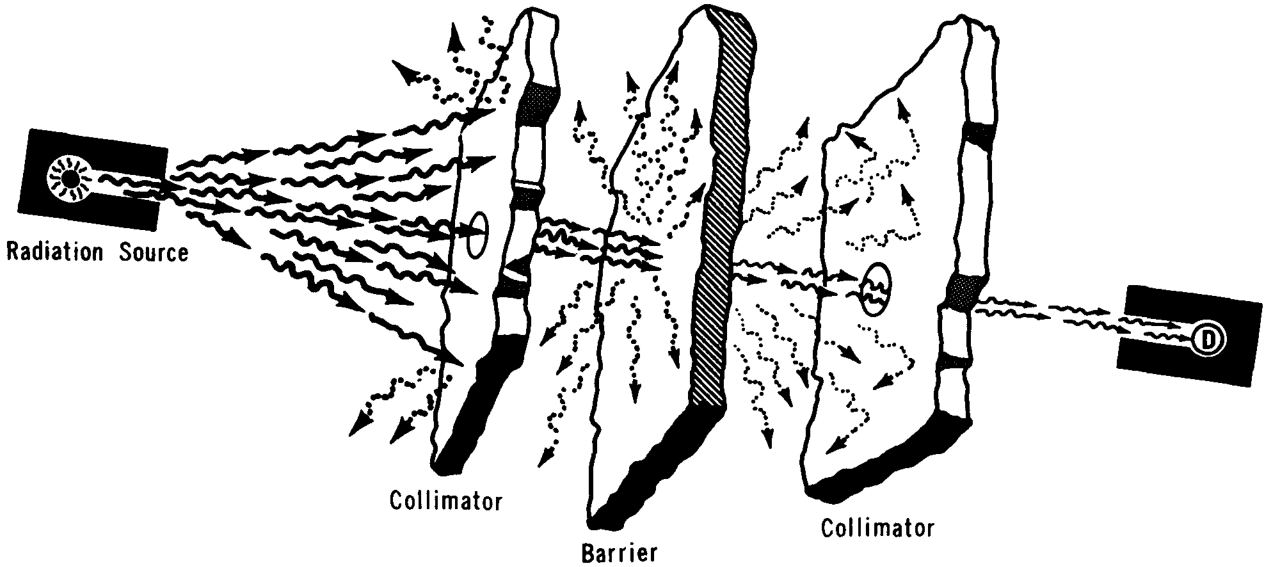


(A.) PLANE DIAGRAM

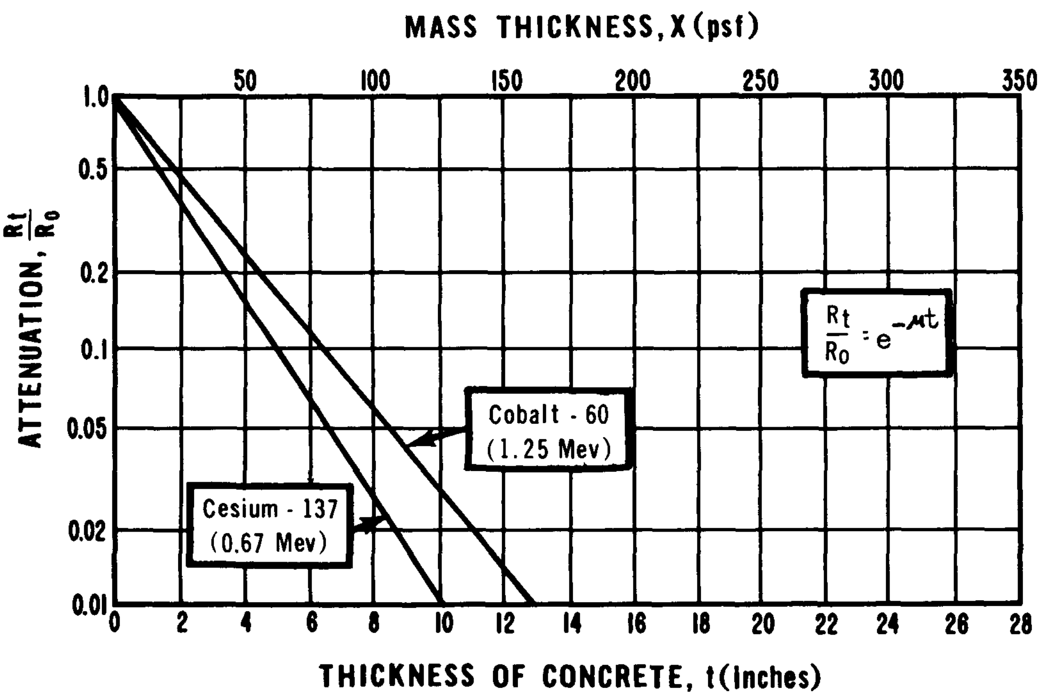


(B.) POLAR DIAGRAM (Detector 30 feet above contaminated plane)

Fig. 10. Directional Distribution (Plane Case)



(A.) TEST ARRANGEMENT



(B.) TEST RESULTS

Fig. 11. Narrow Beam Test

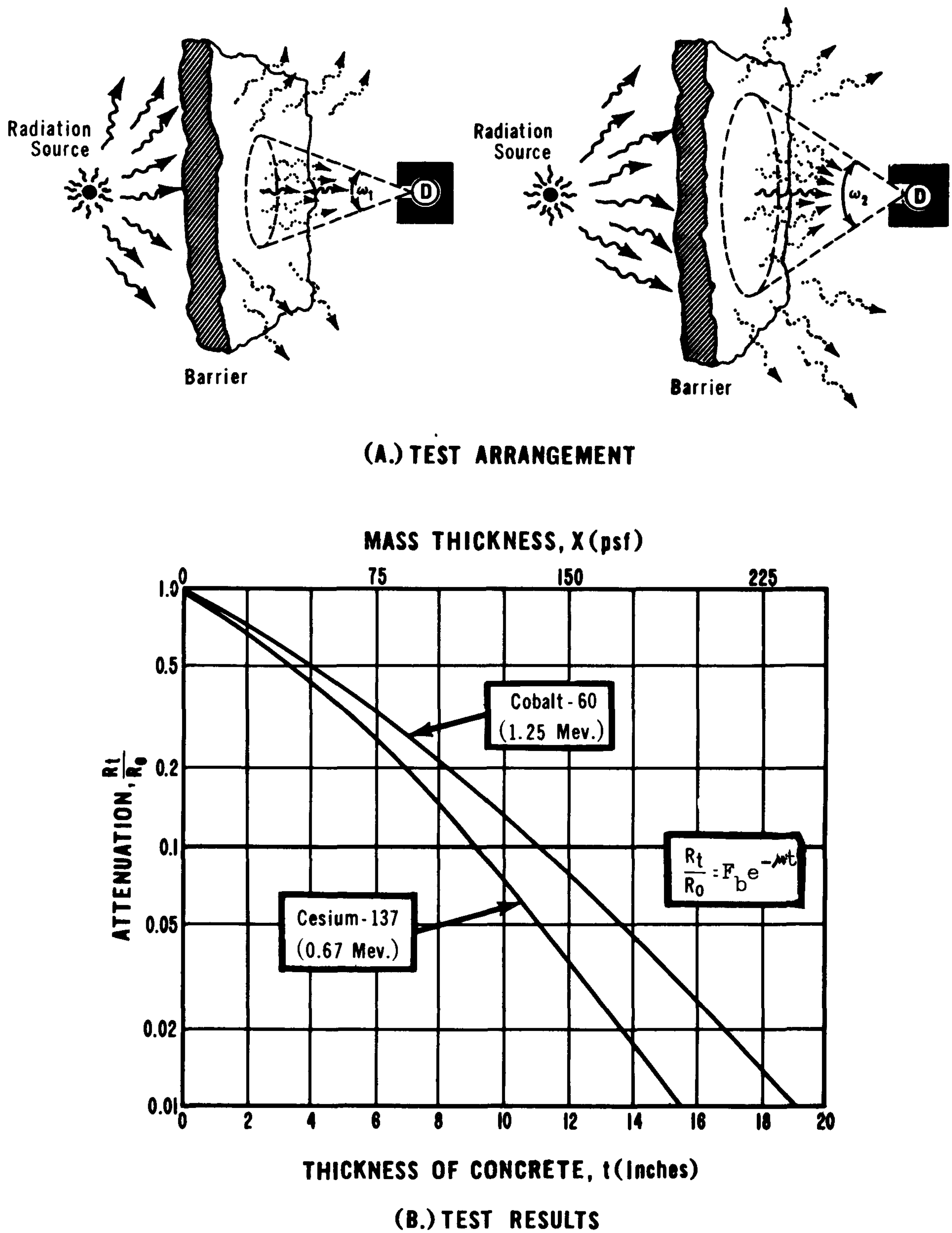
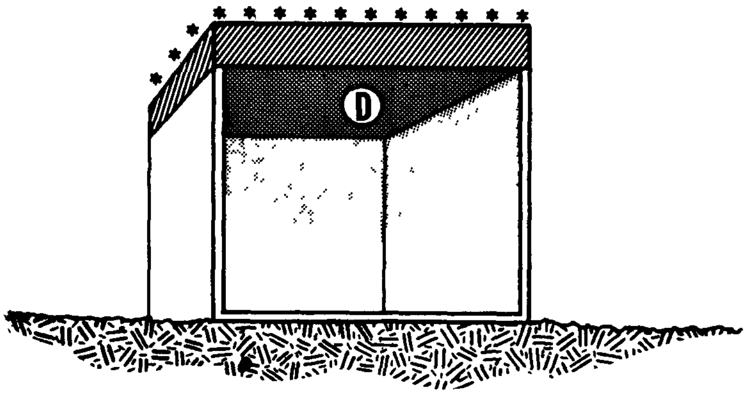
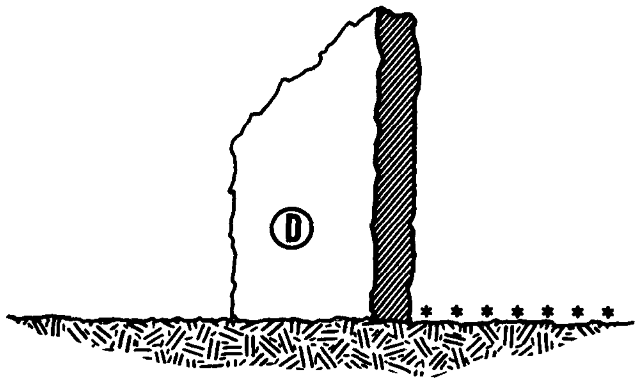


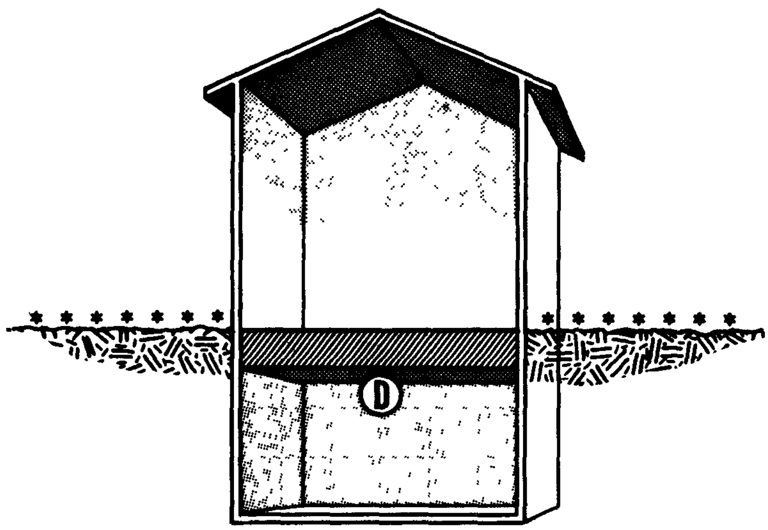
Fig. 12. Broad Beam Test



(A.) CASE 1 - FALLOUT ON BARRIER

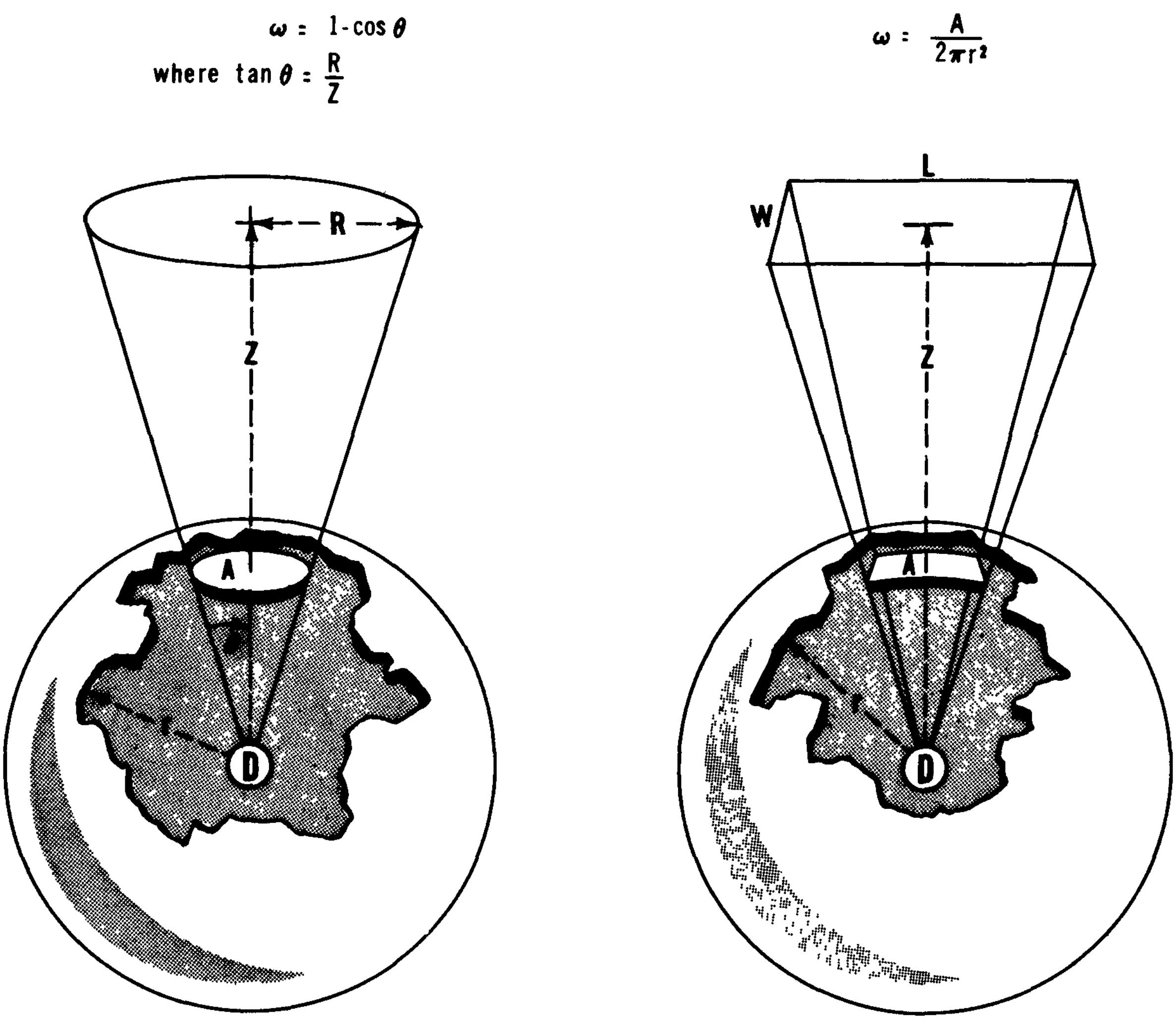


(B.) CASE 2 - FALLOUT ADJACENT TO VERTICAL BARRIER



(C.) CASE 3 - FALLOUT ADJACENT TO HORIZONTAL BARRIER

Fig. 13. Barrier Shielding Effects



(A.) CIRCULAR AREA **(B.) RECTANGULAR AREA**

Fig. 14. Solid Angle Fraction, ω

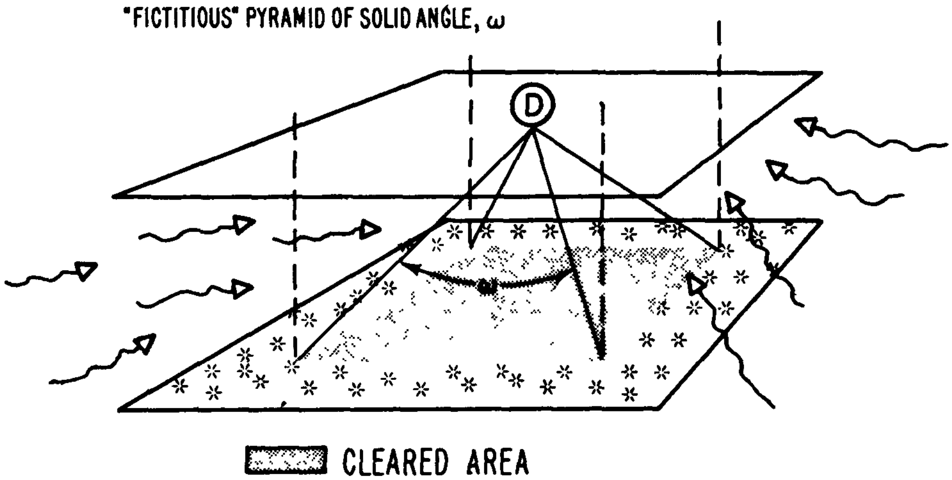


Fig. 15. Directional Responses

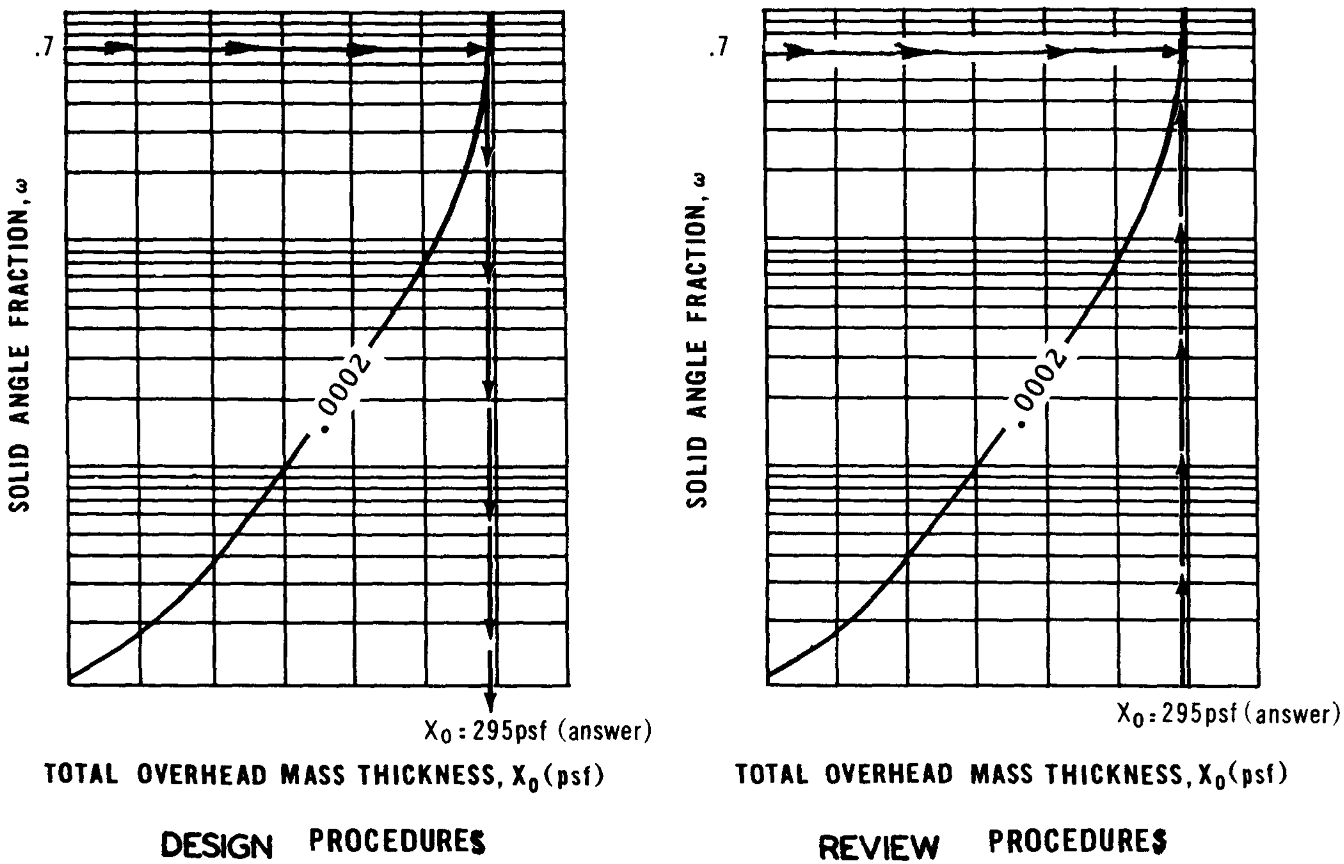


Fig. 16. Use of Chart 4

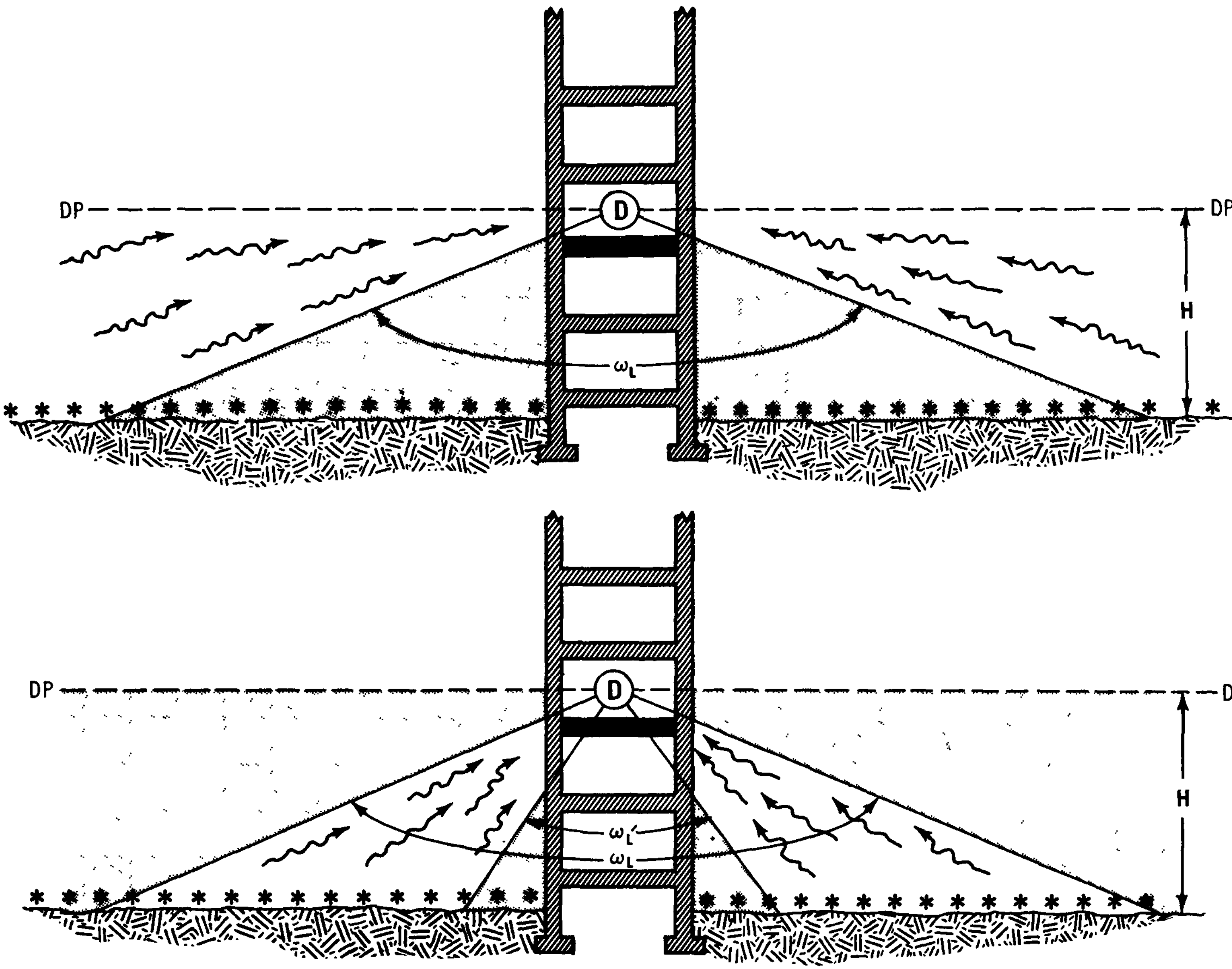


Fig. 17. Variation of G_d with Height

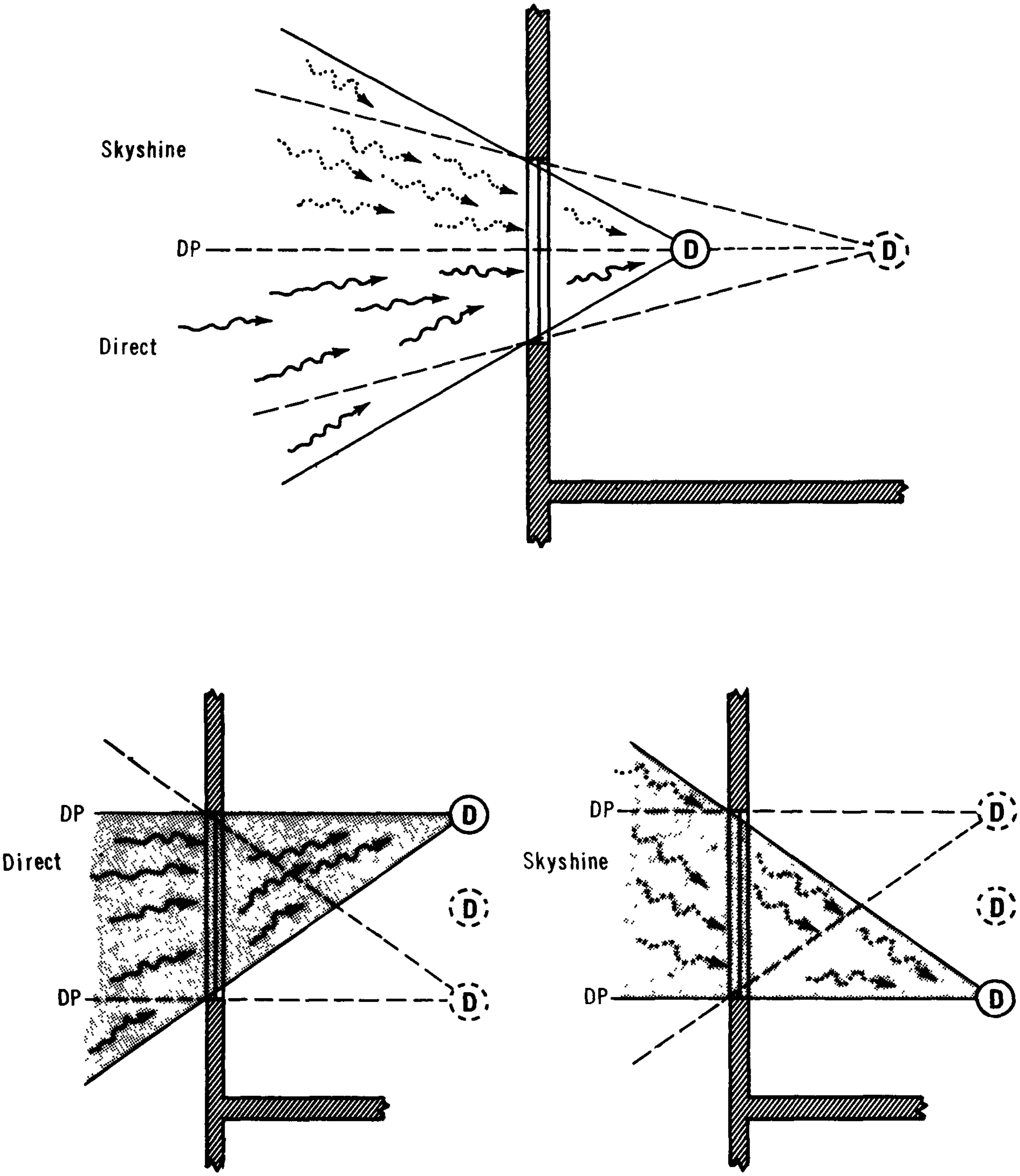


Fig. 18. Effect of Windows on Wall Barriers

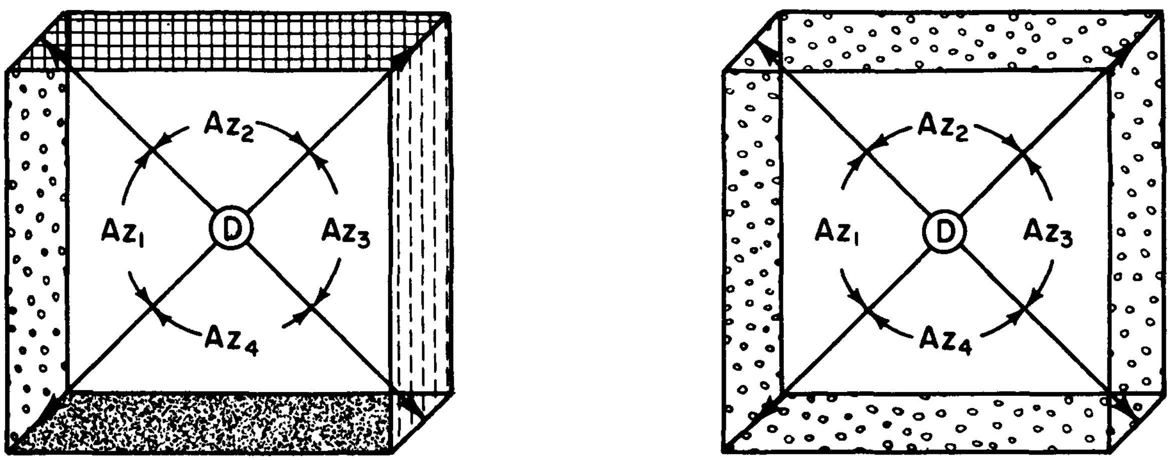


Fig. 19. Sector Analysis (Long Wall Areas)

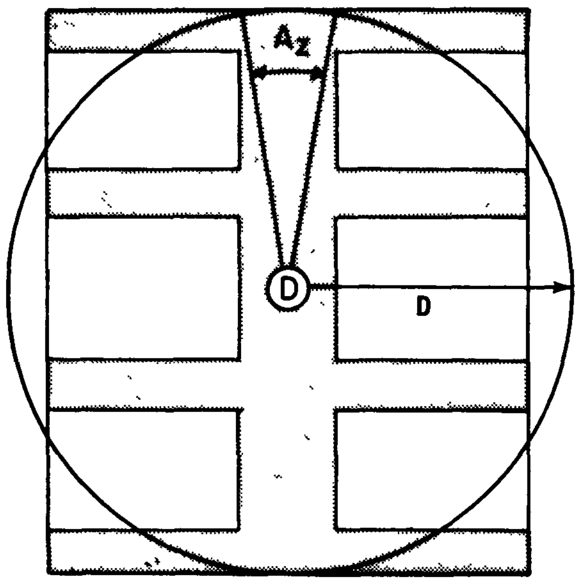


Fig. 20. Sector Analysis (Short Wall Areas)

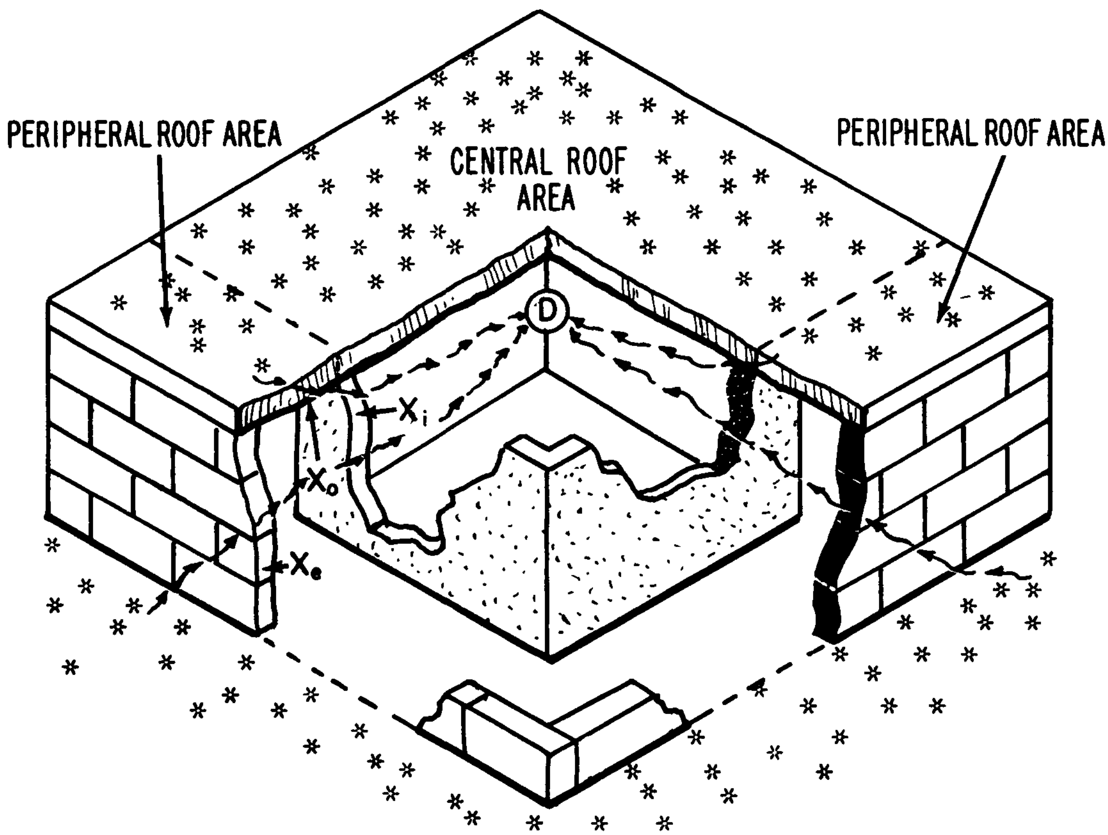


Fig. 21. Parallel Interior Partitions

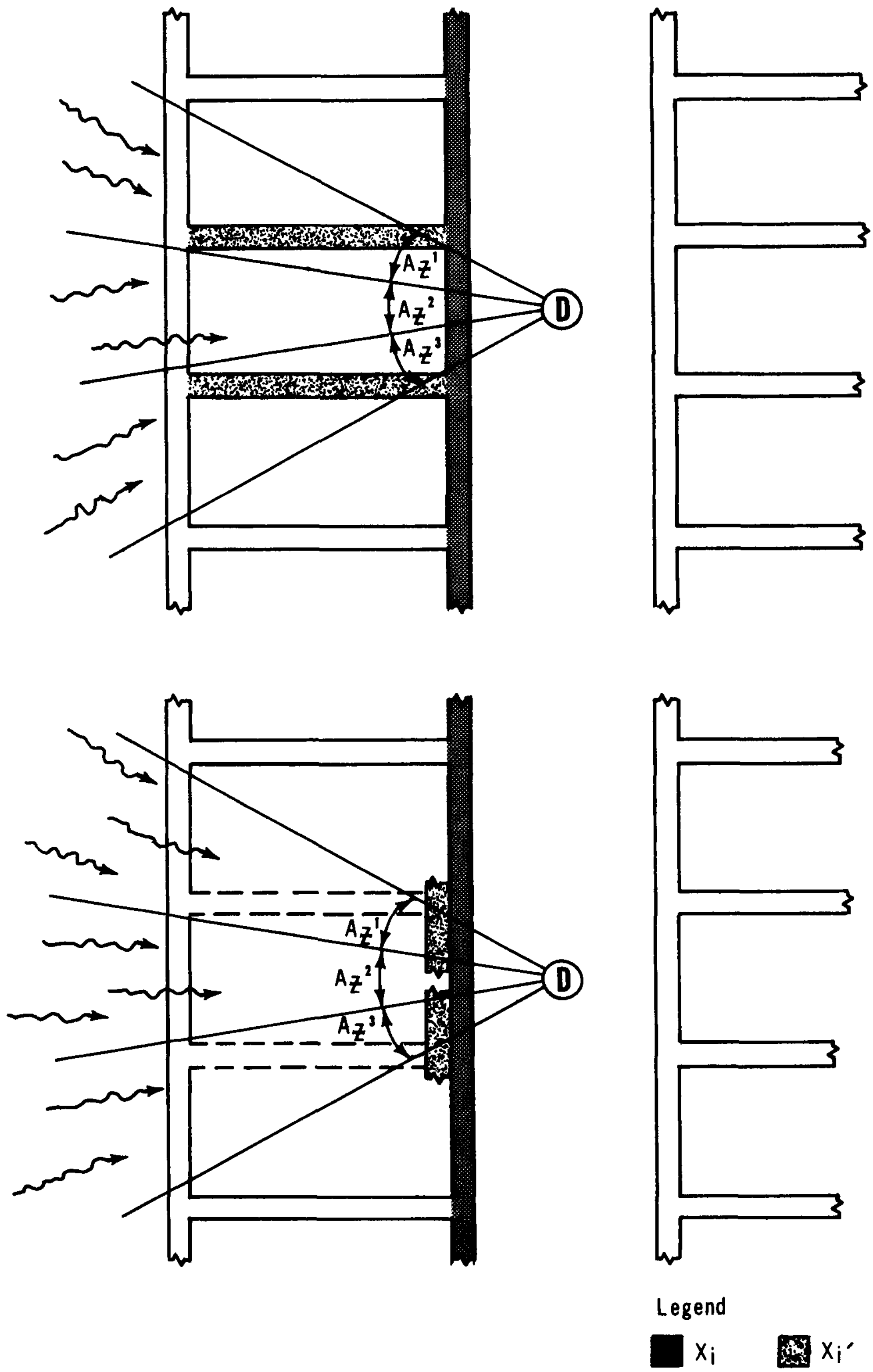


Fig. 22. Perpendicular Interior Partitions

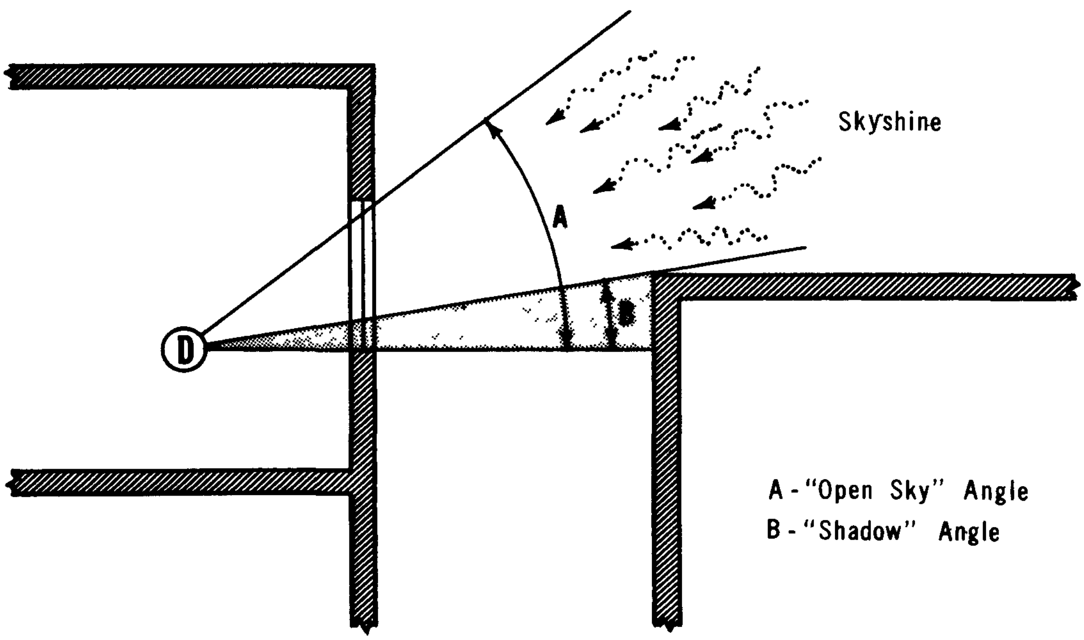


Fig. 23. Effect of Adjacent Buildings on Skyshine Contribution

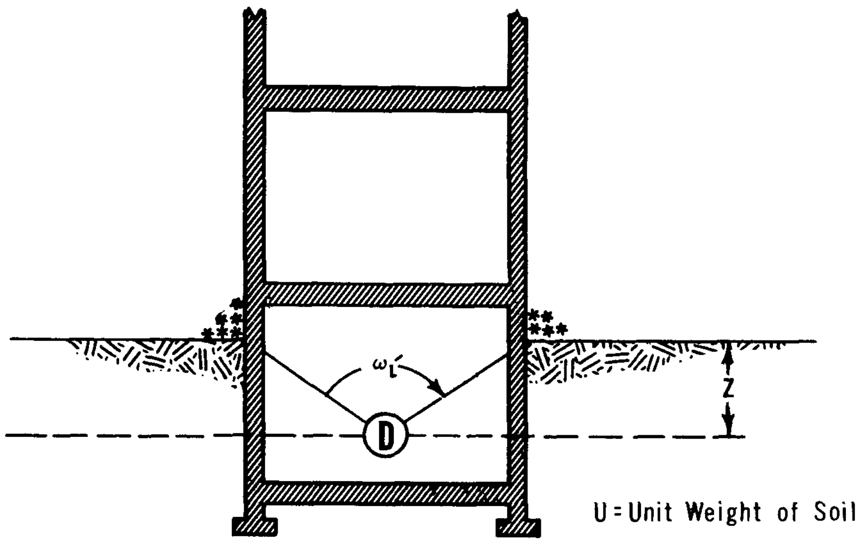


Fig. 24. Fallout Particle Pile-up on Foundation Walls

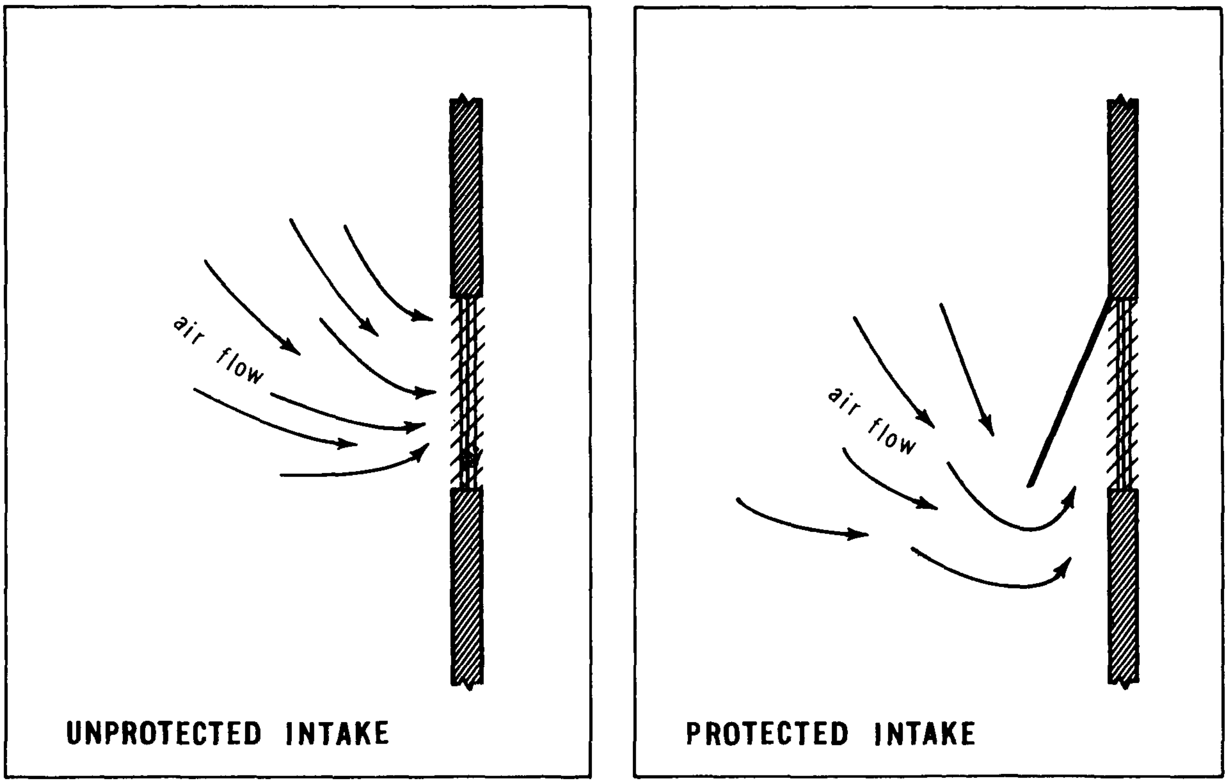
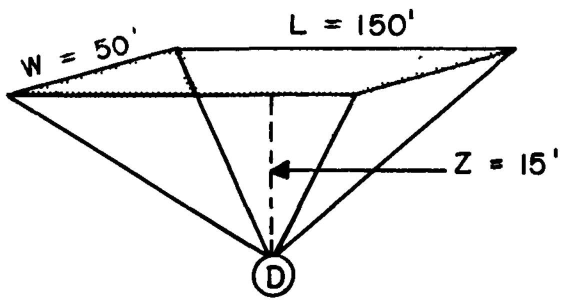


Fig. 25. Air Intakes for Group Shelters

SOLID ANGLE FRACTIONS

Example No. 1

a. Detector along perpendicular axis at center of rectangle

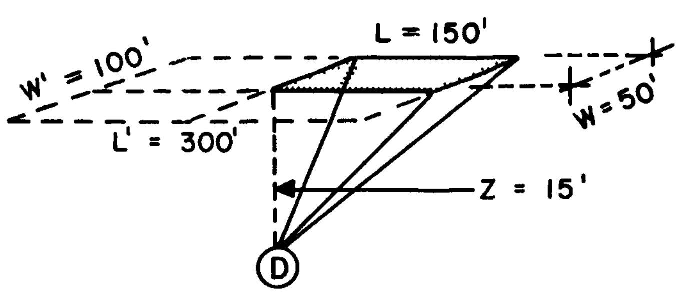


$$e = \frac{W}{L} = \frac{50'}{150'} = .33$$

$$n = \frac{2Z}{L} = \frac{30'}{150'} = .20$$

$$\omega = \underline{\underline{.63}} \quad \text{answer}$$

b. Detector along perpendicular axis at corner of rectangle



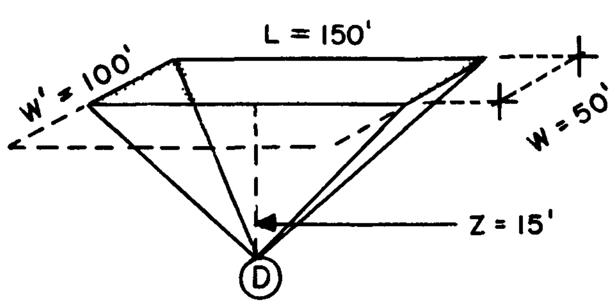
$$e' = \frac{W'}{L'} = \frac{100'}{300'} = .33$$

$$n' = \frac{2Z}{L'} = \frac{30'}{300'} = .10$$

$$\omega' = .80$$

$$\omega = \frac{\omega'}{4} = \frac{.80}{4} = \underline{\underline{.20}} \quad \text{answer}$$

c. Detector along perpendicular axis at center of side



$$e' = \frac{W'}{L} = \frac{100'}{150'} = .67$$

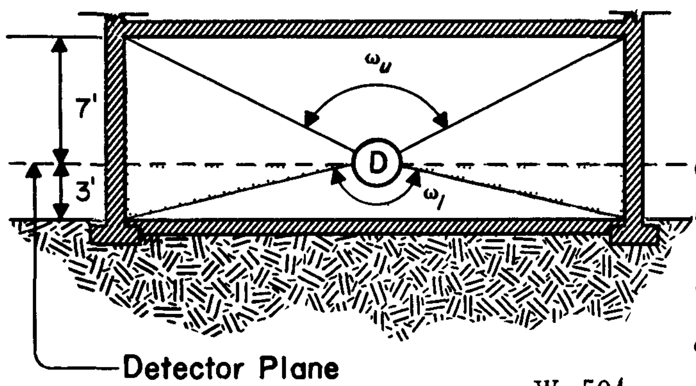
$$n = \frac{2Z}{L} = \frac{30'}{150'} = .20$$

$$\omega' = .78$$

$$\omega = \frac{\omega'}{2} = \underline{\underline{.39}} \quad \text{answer}$$

COMBINING AND DIFFERENCING DIRECTIONAL RESPONSES
Example No. 2

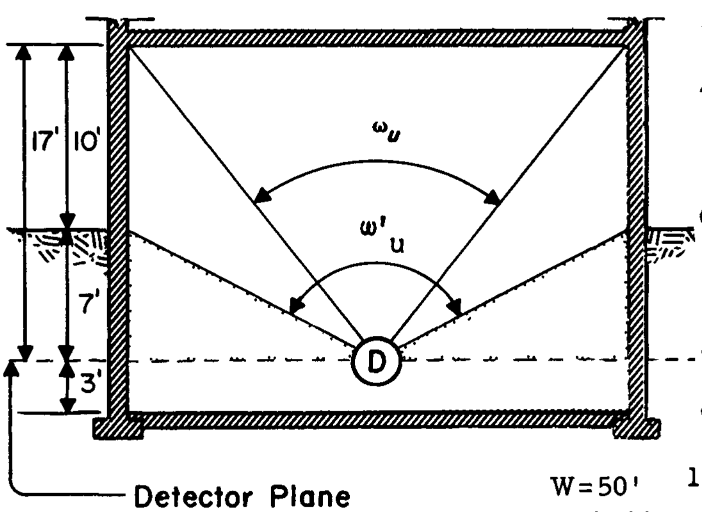
a. Detector above ground



W=50'
L=100'

1. $e_u = e_\ell = \dfrac{W}{L} = \dfrac{50'}{100'} = .50$
2. $n_u = \dfrac{2\ Z_u}{L} = \dfrac{2 \times 7'}{100'} = .14$
3. $n_\ell = \dfrac{2\ Z_\ell}{L} = \dfrac{2 \times 3'}{100'} = .06$
4. $\omega_u\ (e_u, n_u) = .80$
5. $\omega_\ell\ (e_\ell, n_\ell) = .91$
6. $G_s\ (\omega_u) = .21$
7. $G_s\ (\omega_\ell) = \underline{.097}$
8. Combined Response $= .307$ say $\underline{\underline{.31}}$ answer
9. $G_a\ (\omega_u) = .055$
10. $G_d\ (\omega_\ell) = \underline{.37}$
11. Combined Response $= .425$ say $\underline{\underline{.42}}$ answer

b. Detector below ground



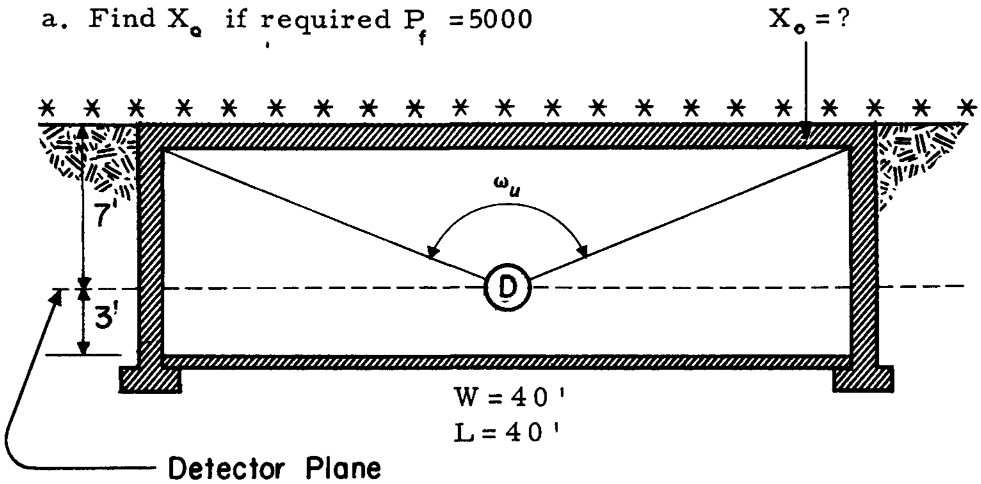
W=50'
L=100'

1. $e_u = e'_u = \dfrac{W}{L} = \dfrac{50'}{100'} = .50$
2. $n_u = \dfrac{2\ Z_u}{L} = \dfrac{2 \times 17'}{100'} = .34$
3. $n'_u = \dfrac{2\ Z'_u}{L} = \dfrac{2 \times 7'}{100'} = .14$
4. $\omega_u\ (e_u, n_u) = .57$
5. $\omega'_u\ (e'_u, n'_u) = .80$
6. $G_s\ (\omega_u) = .35$
7. $G_s\ (\omega'_u) = .21$
8. Differenced Response $= \underline{\underline{.14}}$ answer
9. $G_a\ (\omega_u) = .081$
10. $G_a\ (\omega'_u) = \underline{.053}$
11. Differenced Response $= .028$ say $\underline{\underline{.03}}$ answer

SIMPLE UNDERGROUND SHELTER

Example No. 3

a. Find X_o if required P_f =5000



1. $e = \frac{W}{L} = \frac{40'}{40'} = 1.0$

2. $n = \frac{2Z}{L} = \frac{2 \times 7'}{40'} = .35$

3. $\omega_u = .70$

4. $R_f = \frac{1}{P_f} = \frac{1}{5000} = .0002$

5. $X_o = \underline{\underline{295}}$ psf answer

b. Find depth of earth cover if shelter roof slab is 8" reinforced concrete and the in-place unit weight compacted earth is 120pcf.

1. X (roof slab) = 8" x 12-1/2 psf per inch = 100 psf.

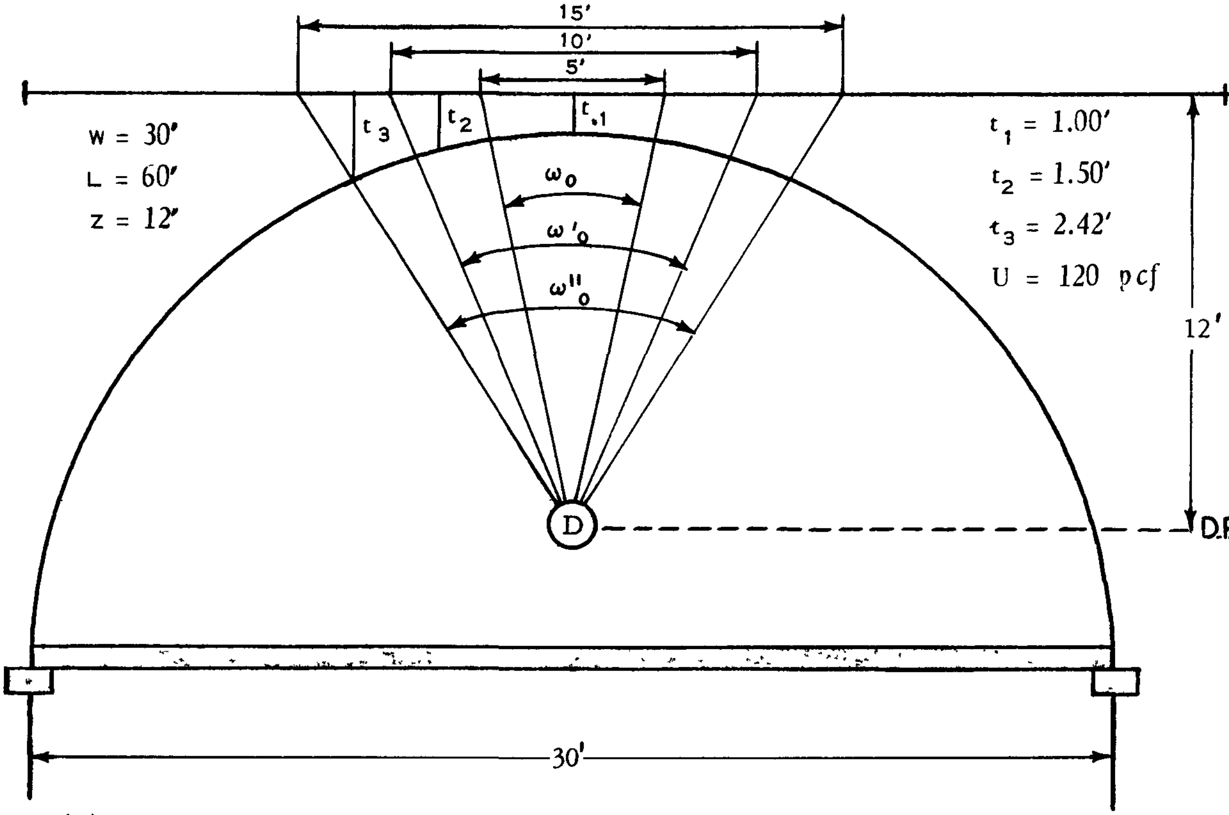
2. Req'd X (earth cover) = 295 psf - 100 psf = 195 psf.

3. Depth of earth cover = $\frac{195 \text{ psf}}{120 \text{ pcf}}$ = 1.62 ft.

say $\underline{\underline{1'\text{-}8''}}$ answer

SIMPLE UNDERGROUND ARCH SHELTER

Example No. 3(c)



1. (a) $X_o = t_1 U = 1.00' \times 120 \text{ pcf} = 120 \text{ psf}$

   (b) $X'_o = t_2 U = 1.50' \times 120 \text{ pcf} = 180 \text{ psf}$

   (c) $X''_o = t_3 U = 2.42' \times 120 \text{ pcf} = 290 \text{ psf}$

2. (a) $n_o = n'_o = n''_o = \frac{2 \times 12'}{60'} = .40$ (c) $e'_o = \frac{10'}{60'} = .17$ or $\omega'_o = .25$

   (b) $e_o = \frac{5'}{60'} = .08$ or $\omega_o = .13$ (d) $e''_o = \frac{15'}{60'} = .25$ or $\omega''_o = .34$

3. $C_o (\omega_o, X_o) = .0045$

4. $C_o (\omega'_o, X'_o) - C_o (\omega_o, X'_o) = .0020 - .0013 = .0007$

5. $C_o (\omega''_o, X''_o) - C_o (\omega'_o, X''_o) = .00021 - .00019 = .00002$

6. $R_f = (3) + (4) + (5) = .0045 + .0007 + .00002 = .00522$

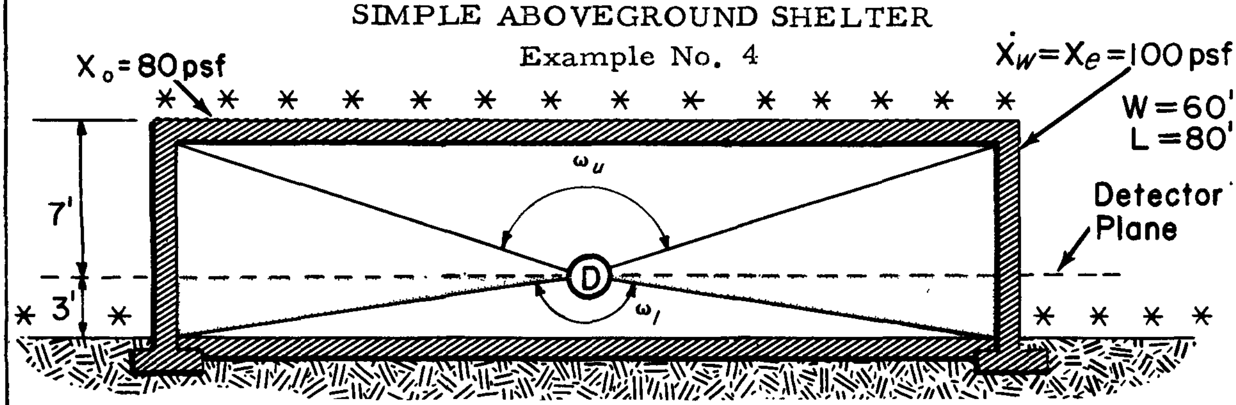
7. Contribution by Zones

   (a) Zone (ω_o) = 85% (c) Zone (ω''_o) = 100%

   (b) Zone (ω'_o) = 99½%

SIMPLE ABOVEGROUND SHELTER

Example No. 4



1. $e_u = e_\ell = \frac{W}{L} = \frac{60'}{80'} = .75$

2. $n_u = \frac{2\ Z_u}{L} = \frac{2 \times 7'}{80'} = .175$ say $.18$

   and $n_\ell = \frac{2\ Z_\ell}{L} = \frac{2 \times 3'}{80'} = .075$

3. $\omega_u\ (e_u, n_u) = .81$ and $\omega_\ell\ (e_\ell, n_\ell) = .92$

4. $G_s\ (\omega_u) = .20$ and $G_s\ (\omega_\ell) = .085$

5. Also, $B_w\ (X_w, H) = .095$; $S_w\ (X_w) = 74\%$

   and $E\ (e_\ell) = 1.40$

6. Wall-scattered: $G_g = [G_s\ (\omega_u) + G_s\ (\omega_\ell)]\ S_w \times E$

   $= (.20 + .085).74 \times 1.40 = .29$

7. $G_a\ (\omega_u) = .053$ and $G_d\ (\omega_\ell) = .35$

8. Non-wall scattered: $G_g = [G_a\ (\omega_u) + G_d\ (\omega_\ell)]\ (1\text{-}S_w)$

   $= (.053 + .35)\ (1-.74) = .10$

9. Total $C_g = [(6) + (8)]\ B_w\ (X_w, H)$

   $= (.29 + .10)\ .088 = .034$

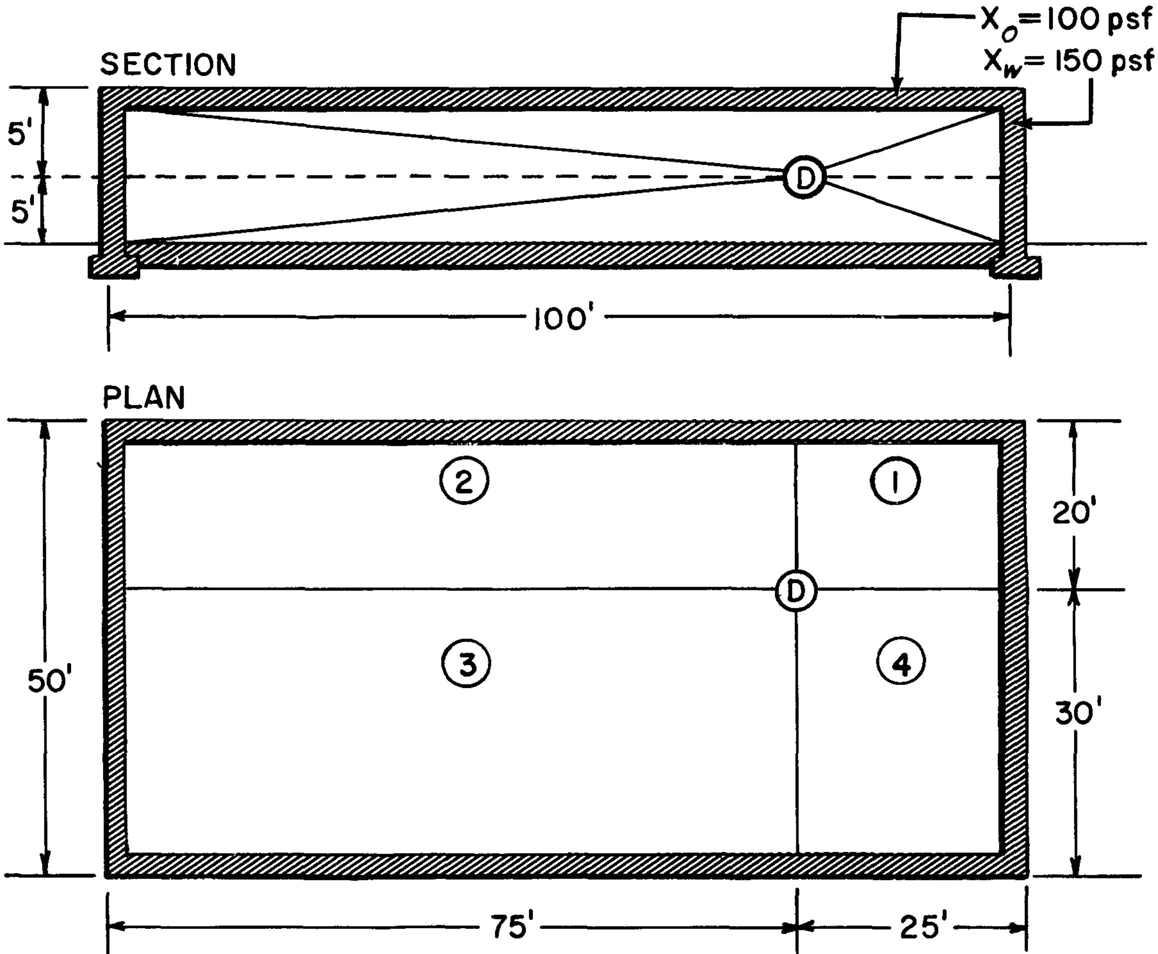
10. Roof Contribution, $C_o\ (\omega_u, X_o) = .034$

11. Total Reduction Factor, $R_f = C_o + C_g =$

    $.034 + .034 = .068$ answer

DETECTOR POSITION VARIATIONS

Example No. 5



1. Quadrant ①

(a) $e_u = e_\ell = \frac{20'}{25'} = .8$; $n_u = n_\ell = \frac{5'}{25'} = .2$; $\omega_u = \omega_\ell = .80$

(b) $G_a = .055$, $G_d = .57$, $G_s = .21$, $E = 1.41$, $C_o = .019$

2. Quadrant ②

(a) $e_u = e_\ell = \frac{20'}{75'} = .27$; $n_u = n_\ell = \frac{5'}{75'} = .067$; $\omega_u = \omega_\ell = .84$

(b) $G_a = .047$, $G_d = .52$, $G_s = .18$, $E = 1.22$, $C_o = .019$

DETECTOR POSITION VARIATION

Example No. 5 (con't)

3. Quadrant 3

(a) $e_u = e_\ell = \frac{30'}{75'} = .40;\ n_u = n_\ell = \frac{5'}{75'} = .067;\ \omega_u = \omega_\ell = .89$

(b) $G_a = .034,\ G_d = .43,\ G_s = .12,\ E = 1.30,\ C_o = .019$

4. Quadrant 4

(a) $e_u = e_\ell = \frac{25'}{30'} = .83;\ n_u = n_\ell = \frac{5'}{30'} = .167;\ \omega_u = \omega_\ell = .83$

(b) $G_a = .049,\ G_d = .53,\ G_s = .18,\ E = 1.41,\ C_o = .019$

5. Non-Wall scattered Geometry Factor

$$\frac{1}{4}\,[G_a\,1 + G_a\,2 + G_a\,3 + G_a\,4 +$$

$$G_d\,1 + G_d\,2 + G_d\,3 + G_d\,4\,]\,(1-S_w)$$

$$= \frac{1}{4}\,(.055 + .047 + .034 + .049 +$$

$$.57 + .52 + .43 + .53).19 = .11$$

6. Wall-scattered Geometry Factor

$$2 \times \frac{1}{4}\,[G_s\,1\,E\,1 + G_s\,2\,E\,2 + G_s\,3\,E\,3 +$$

$$G_s\,4\,E\,4\,]\,S_w$$

$$\frac{1}{2}\,(.21 \times 1.41 + .18 \times 1.22 + .12 \times 1.30 + .18 \times 1.41)\,S_w$$

$$\frac{1}{2} \times .93 \times .81 = .37$$

7. $C_g = [(5) + (6)]\,B_w = (.11 + .37)\ .025 = .014$

8. $C_o = \frac{1}{4}\,[C_o\,1 + C_o\,2 + C_o\,3 + C_o\,4\,]$

$$= \frac{1}{4}\,(.019 + .019 + .019 + .019) = .019$$

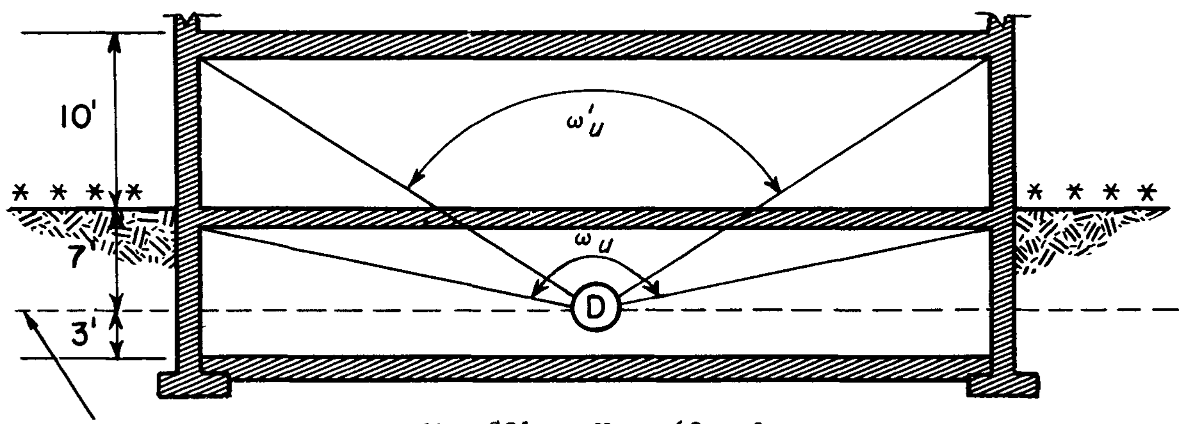
9. $R_f = C_g + C_o = .014 + .019 \doteq .033$

10. $P_f = \frac{1}{R_f} = \underline{\underline{30}}$ answer

SIMPLE BASEMENT SHELTER

Example No. 6

a. Basement Wall, unexposed



W = 80' X_w = 60 psf

L = 140' X_o = 330 psf

X'_o = 80 psf

1. $e_u = e'_u = \frac{80'}{140'} = .57$; $n_u = \frac{14'}{140'} = .1$; $n'_u = \frac{34'}{140'} = .24$

2. $\omega_u = .87$; $\omega'_u = .70$

3. $[G_s(\omega'_u) - G_s(\omega_u)]\, S_w E = (.29 - .15) \times .62 \times 1.36 = .12$

4. $[G_a(\omega'_u) - G_a(\omega_u)]\, (1 - S_w) = (.070 - .040) \times .38 = .011$

5. $G_g = (3) + (4) = .12 + .011 = .13$

6. $C_g = G_g B_w B'_o = .13 \times .22 \times .017 = .00049$

7. By inspection, C_o is much less than .0001

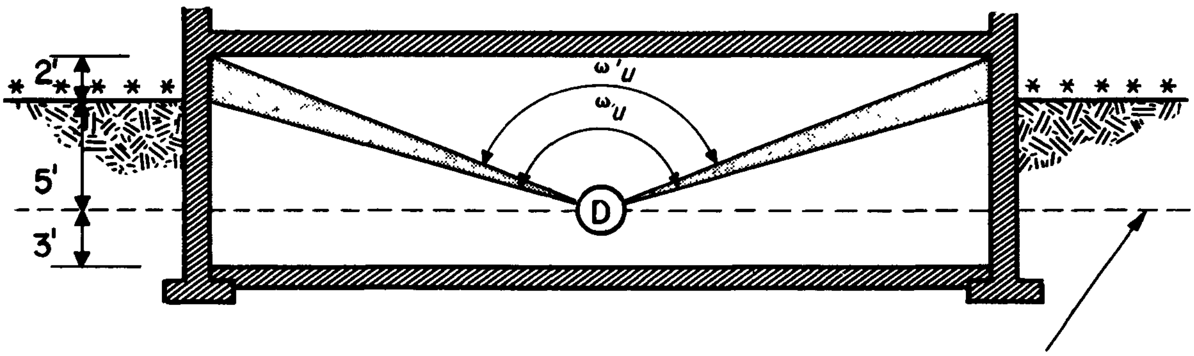
8. $R_f = C_g + C_o = .00049$

9. P_f = 2040 answer

SIMPLE BASEMENT SHELTER

Example No. 6 (con't)

b. Basement wall, exposed



W=80'
L=140'

X_b =80psf

1. $e_u = e'_u = .57$; $n_u = \frac{10'}{140'} = .071$; $n'_u = \frac{14'}{140'} = .10$

2. $\omega_u = .90$; $\omega'_u = .87$

3. $[G_s(\omega'_u) - G_s(\omega_u)]\ S_w E = (.15 - .115)\ .69 \times 1.36 = .033$

4. $[G_a(\omega'_u) - G_a(\omega_u)]\ (1-S_w) = (.040 - .031)\ .31 = .0028$

5. $C_g = [(3) + (4)]\ B_w = (.033 + .0028)\ .15 = .0054$

6. C_g (1st Floor Wall) = .00049 & C_o is negligible

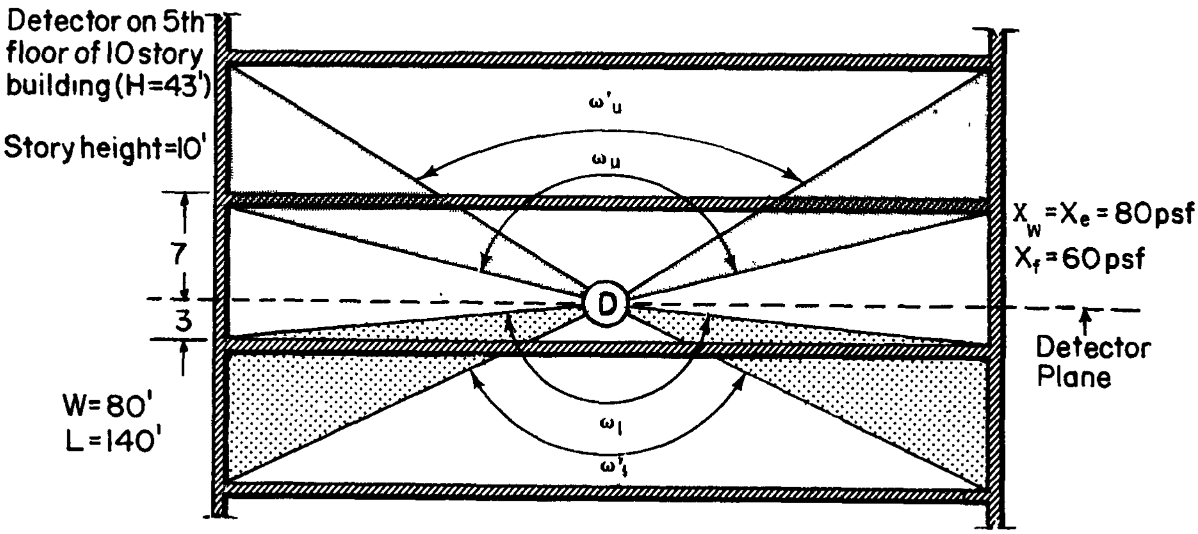
7. $R_f = C_g$ (Basement) + C_g (1st Floor Wall) + C_o

   $= .0054 + .00049 + 0 = .0059$

8. $P_f = \underline{\underline{170}}$ answer

SIMPLE ABOVEGROUND SHELTER (Multistory Building)

Example No. 7



1. $e_u = e'_u = e_\ell = e'_\ell = \frac{80'}{140'} = 0.57$

2. $n_u = \frac{14'}{140'} = .10; \; n'_u = \frac{34'}{140'} = .24$

   $n_\ell = \frac{6'}{140'} = .043; \; n'_\ell = \frac{26'}{140'} = .19$

3. $\omega_u = .87; \; \omega'_u = .70; \; \omega_\ell = .94; \; \omega'_\ell = .76$

4. C_g (Through 5th floor wall)

   a. $[G_s(\omega_u) + G_s(\omega_\ell)] \, S_w \, E =$

   $(.15 + .075) \; .69 \times 1.36 = .22$

   b. $[G_a(\omega_u) + G_d(\omega_\ell, H)] \, (1-S_w) =$

   $(.039 + .03) \; .31 = .021$

   c. $G_g = (4a) + (4b) = .22 + .021 = .24$

   d. $C_g = G_g \, B_w(X_e, H) = .24 \times .077 = .018$

SIMPLE ABOVEGROUND SHELTER (Multistory Building)

Example No. 7 (con't)

5. C_g (Through 6^{th} floor wall)

   a. $[G_s(\omega'_u) - G_s(\omega_u)]\, S_w\, E =$

   $(.29 - .15)\ .69 \times 1.36 = .13$

   b. $[G_a(\omega'_u) - G_a(\omega_u)]\,(1-S_w) =$

   $(.070 - .039).31 = .0096$

   c. $G_g = (5a) + (5b) = .13 + .01 = .14$

   d. $C_g = G_g\, B_w(X_e, H)\, B'_o(X_f) =$

   $.14 \times .066 \times .04 = .00037$

6. C_g (Through 4^{th} floor wall)

   a. $[G_s(\omega'_\ell) - G_s(\omega_\ell)]\, S_w\, E =$

   $(.25 - .075)\ .69 \times 1.36 = .16$

   b. $[G_d(\omega'_\ell, H) - G_d(\omega_\ell, H)]\,(1-S_w) =$

   $(.27 - .03)\ .31 = .074$

   c. $G_g = (6a) + (6b) = .16 + .074 = .23$

   d. $C_g = G_g\, B_w(X_e, H)\, B_o(X_f) =$

   $.23 \times .08 \times .06 = .0011$

7. Roof Contribution

   a. $X_o = 6 \times 60$ psf $= 360$ psf

   b. $B_o(X_o) =$ Less than $.0001$

8. $R_f = (4d) + (5d) + (6d) + (7d) =$

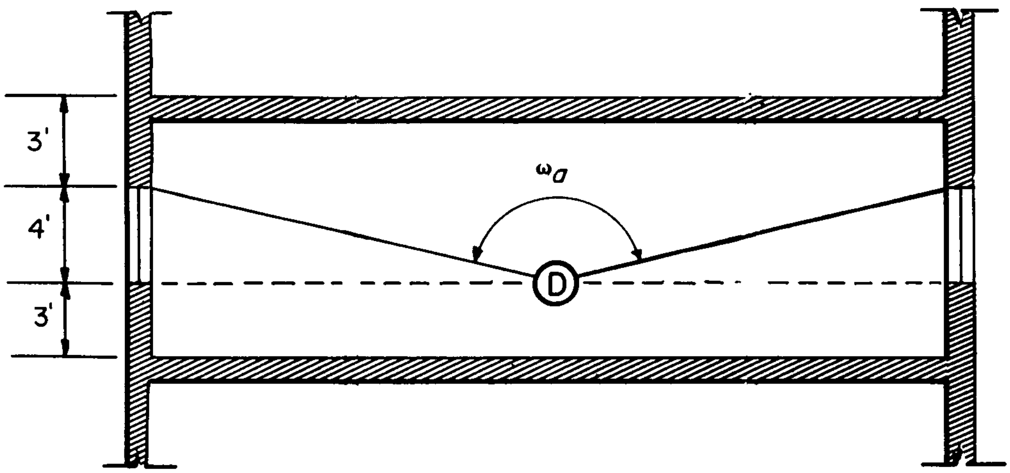
   $.018 + .00037 + .0011$

   $+ .0001 = .020$

9. $P_f = \dfrac{1}{R_f} = \underline{\underline{50}}$ answer

APERTURES (DETECTOR AT SILL LEVEL)

Example No. 8



Same data as example 7 except walls have windows 3' x 4', 6' on centers

1. C'_g (Thru 5^{th} floor wall with windows)

   (a) $e_a = \frac{80'}{140'} = .57$; $n_a = 2 \times \frac{4'}{140'} = .057$ and $\omega_a = .92$

   (b) For "solid wall", $C_g = .018$ (see item 4d, example 7)

   (c) For "filled-in windows", $C'_a = B_w (X_e, H) [G_s (\omega_a) S_w E + G_a (\omega_a) (1-S_w)] P_a$

   or $C'_a = .077 [.095 \times .69 \times 1.36 + .026 \times .31] \frac{3'}{6'}$

   $= .077 (.089 + .0081) .5 = .0037$

   (d) For "as-is" windows, $C_a = B_w (X_e = 0, H) [G_a (\omega_a)] P_a$

   $= .52 \times .026 \times .5 = .0068$

   (e) C'_g (Wall with apertures) $= C_g - C'_a + C_a$

   $= .018 - .0037 + .0068$

   or $C'_g = \underline{\underline{.021}}$ answer

APERTURES (DETECTOR AT SILL LEVEL)

Example No. 8 (con't)

2. C'_g (Thru 6^{th} floor wall with windows)

(a) For $A_p = 0\%$, $C_g = .00037$ (see item 5d, example 7)

(b) For $A_p = 100\%$, $C_g = [G_a\ (\omega'_u) - G_a\ (\omega_u)]\ B_w(X_e = 0, H)\ B'_o(X_f)$

$= .031 \times .48 \times .04 = .00060$

(c) $A_p = (3' \times 4') \ / \ (6' \times 10') = \dfrac{12'}{60'} = 20\%$

(d) $C'_g = (2a)\ (1 - \dfrac{A_p}{100}) + (2b)\ (\dfrac{A_p}{100})$

$= .00037 \times .8 + .00060 \times .2 = .00042$

3. C'_g (Thru 4^{th} floor wall with windows)

(a) For $A_p = 0\%$, $C_g = .0011$ (see item 6d, example 7)

(b) For $A_p = 100\%$, $C_g = [G_d\ (\omega'_\ell) - G_d\ (\omega_\ell)]\ B_w\ (X_e = 0, H)\ B_o(X_f)$

$= .24 \times .55 \times .06 = .0079$

(c) $C'_g = (3a)\ (1 - \dfrac{A_p}{100}) + (3b)\ (\dfrac{A_p}{100})$

$= .0011 \times .8 + .0079 \times .2 = .0025$

4. $R_f = (1e) + (2d) + (3c) + C_o$

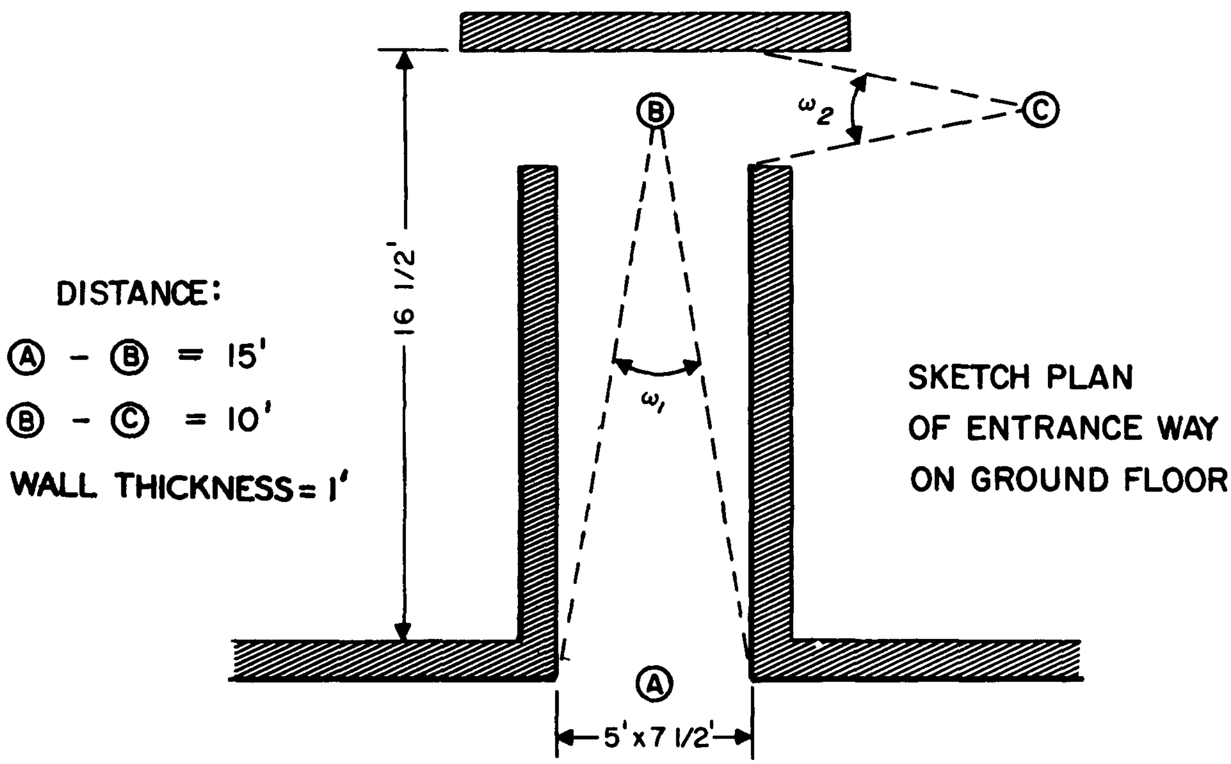
$= .021 + .00043 + .0025 + .0001 = .024$

5. $P_f = \dfrac{1}{R_f} = 42$ say $\underline{\underline{40}}$ answer

PASSAGEWAYS & SHAFTS.

Example No. 9

a. Passageway



1. $e_1 = \frac{5'}{7\frac{1}{2}'} = .67$; $n_1 = 2 \times \frac{15'}{7\frac{1}{2}'} = 4$, $\omega_1 = .024$

2. R_f at Ⓑ $= A_v(\omega_1) = .034$

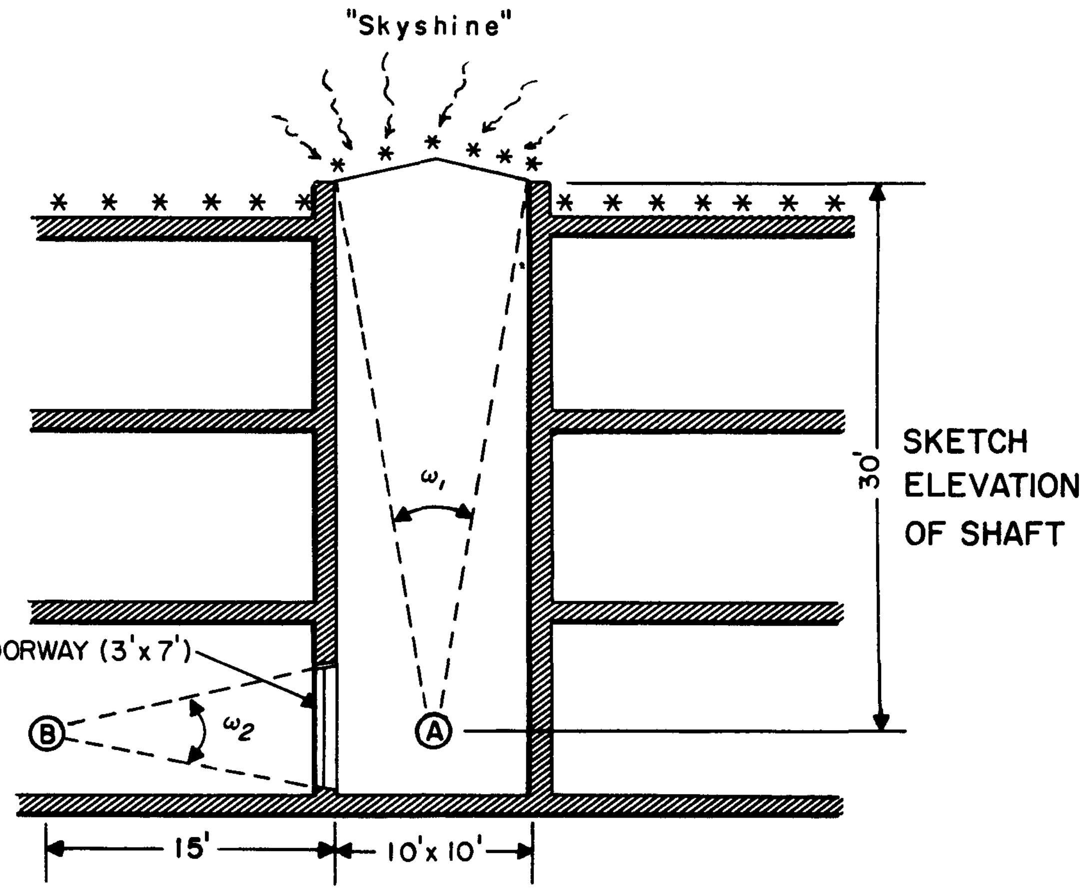
3. $e_2 = e_1 = .67$; $n_2 = 2 \times \frac{(10'-2\frac{1}{2}')}{7\frac{1}{2}'} = 2$; $\omega_2 = .09$

4. R_f at Ⓒ $= (2) \times \omega_2 \times .1 = .034 \times .09 \times .1$

$= \underline{\underline{.00031}}$ answer

Example No. 9 (con't)

b. Shaft



1. $e_1 = \frac{10'}{10'} = 1$; $n_1 = 2 \times \frac{30'}{10'} = 6$; $\omega_1 = .018$

2. R_f at Ⓐ $= A_h\ (\omega_1) + A_a\ (\omega_1) = .0032 + .0008 = .004$

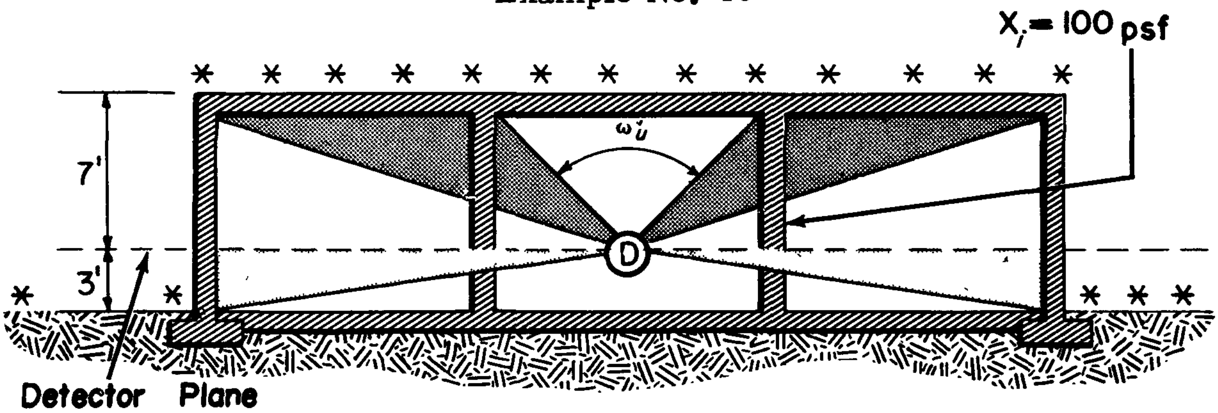
3. $e_2 = \frac{3'}{7'} = .43$; $n_2 = 2 \times \frac{15'}{7'} = 4.3$; $\omega_2 = .015$

4. R_f at Ⓑ $= (2) \times \omega_2 \times .1 = .004 \times .015 \times .1 = \underline{\underline{.000006}}$ answer

SIMPLE ABOVEGROUND SHELTER

Parallel interior partitions

Example No. 10



Same data as example 4 except for central core, W=40', L=60'

1. $e'_u = \frac{W'}{L'} = \frac{40'}{60'} = .67$ $\qquad n'_u = \frac{2Z}{L'} = \frac{2 \times 7'}{60'} = .23$

   $\omega'_u = .72$

2. (a) $C_g(G_g, B_e, B_i) = C_g(G_g, B_e)\, B_i$

   where $C_g(G_g, B_e)$ is from step 9, Example 4

   and B_i (100 psf) = .088

   (b) $C_g(G_g, B_e)\, B_i = .034 \times .088 = .0030$

3. (a) $C_o(\omega'_u, X_o) = .032$

   (b) $C_o(\omega_u, X_o) - C_o(\omega'_o) = .034 - .032 = .002$

   see step 10, Example 4 for $C_o(\omega_u, X_o)$

4. $H_f = 13\, X_o = 13 \times 80$ psf $= 1040'$ (of air)

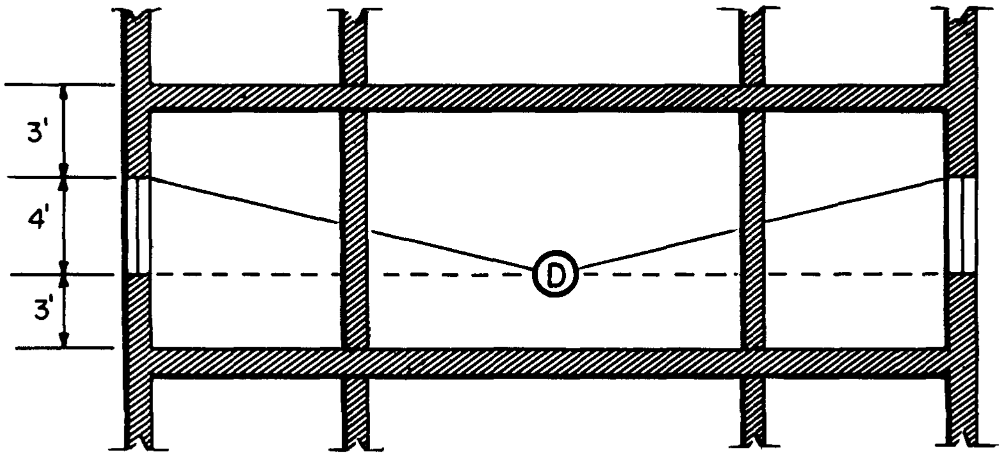
5. C_o (Peripheral Roof Area) = (3b) $\times \frac{B_i(X_i, H_f)}{B_i(0psf, H_f)}$

   $= .002 \times \frac{.002}{.03} = .0001$, negligible

6. R_f = (2b) + (3a) + (5) = .0030 + .032 + negl. = $\underline{\underline{.035}}$ answer

APERTURES (DETECTOR AT SILL LEVEL)
Parallel Interior Partitions

Example No. 11



Same data as examples 7 and 8 except X_i =100psf

1. $B_i (X_i) = .088$

2. $[C'_g(4^{th} \text{ floor}) + C'_g(5^{th} \text{ floor}) + C'_g(6^{th} \text{ floor})] B_i$

$= (.0025 + .021 + .00042)\ .088$

$= .024 \times .088 = .0021$

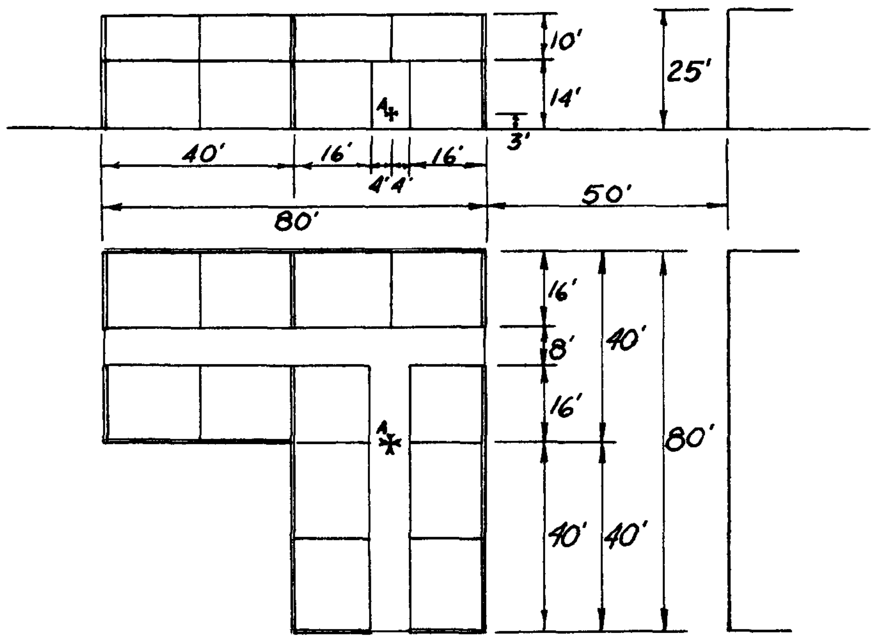
3. $R_f = \text{Total } C'_g + \text{Total } C_o$

$= .0021 + .0001 = .0022$

4. $P_f = \dfrac{1}{R_f} = \underline{\underline{455}}$ answer

SHIELDING ANALYSIS OF A FICTIONAL BUILDING

Example No. 12



Given: Structure, vertically shielded at 50' on one wall.

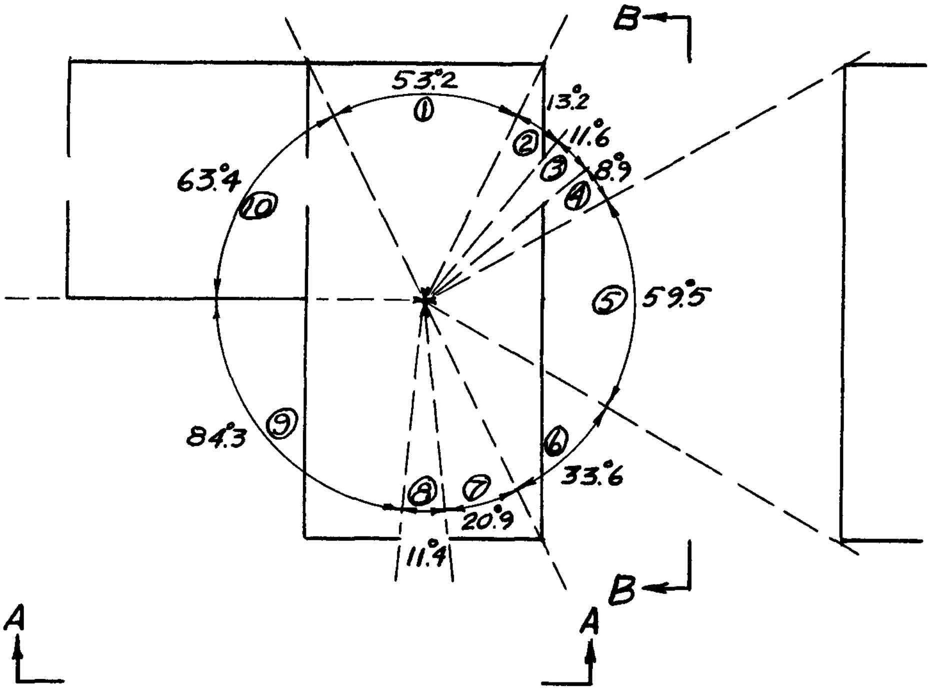
Frame:	Reinforced Concrete
Exterior Walls:	8" Concrete Block
Shear Wall:	8" Concrete Block
Partitions:	Wooden Studs with ½" dry wall
Floor Slabs:	6" Reinforced Concrete
Roof Slab:	4" Reinforced Concrete
Roofing:	5 ply, built up, with gravel
Ceiling:	Acoustical Tile
Windows:	3' wide, x 6', 15% Aperatures Sill height 3'
Doors:	Hollow Core, Wooden, 7' high

Forced air heat with ducts in corridor

Adjacent building, masonary wall bearing with flat roof.

Problem: Determine P. F. of A.

a. Applicable sketches



Sector breakdown for analysis of exterior walls

(1) Find following contributions based on a basic structure with width of 40' and length of 80': Sectors 1,2,4,5,6,7,9 first floor and sectors 1 through 9 second floor. Sector 5 has mutual shielding of direct radiation, first floor. Sectors 2,4,5,6 have mutual shielding of scatter radiation both floors.

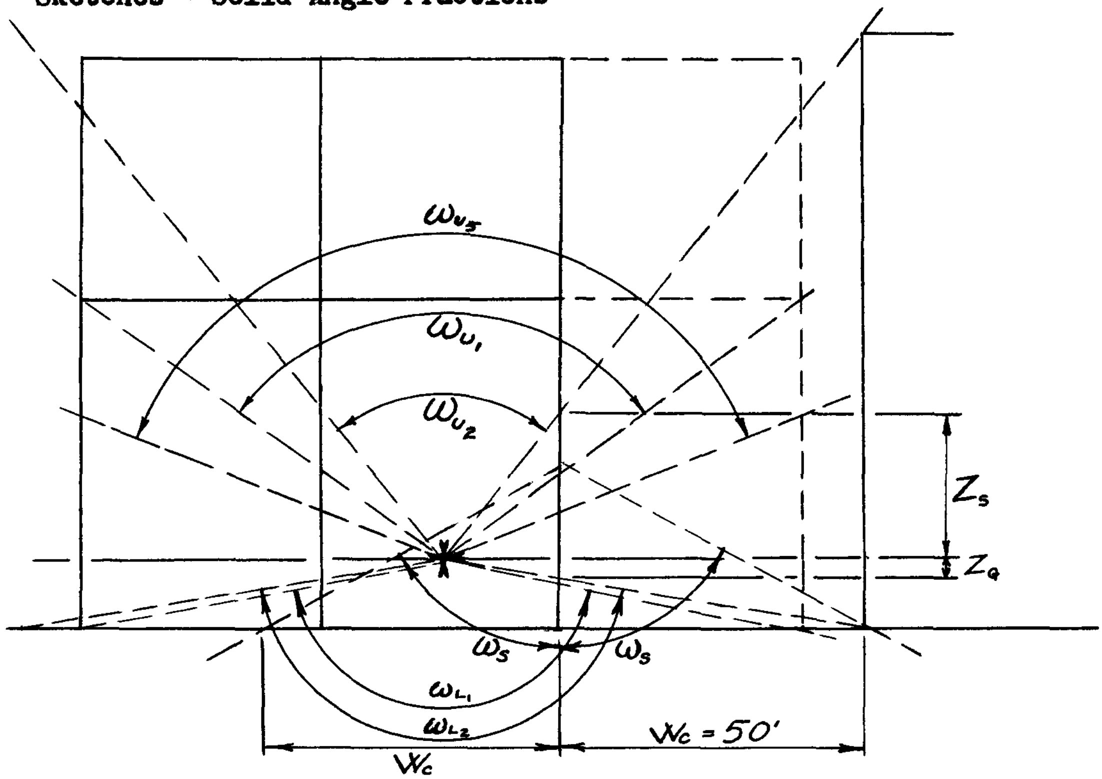
(2) Find following contributions based on reduction factors for passageways:

Sectors 3 and 8 first floor.

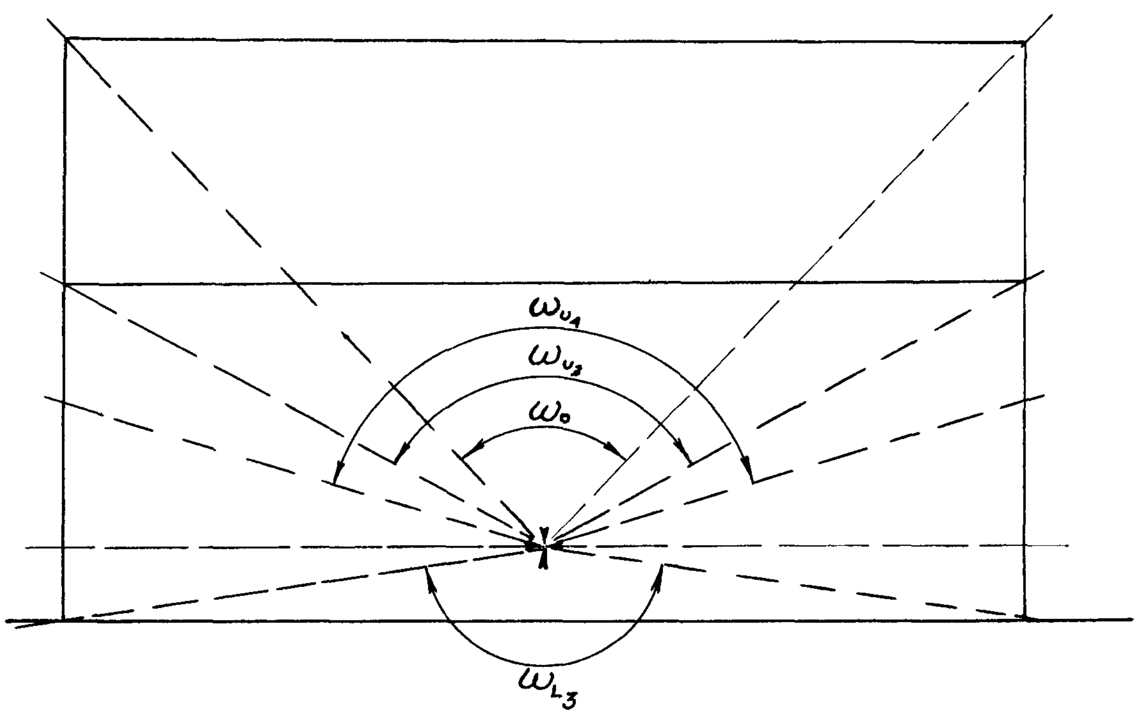
(3) Find following contributions based on a basic structure with width of 80' and length of 120':

Sector 10.

Sketches - Solid Angle Fractions



View A-A



View B -B

Solid Angle Fraction Designations

ω_{u1} - Top of first floor slab of fictitious building 80' x 120' incorporating the wing

ω_{u2} - Top of mutual shielding for use with skyshine direct, use Z_s and core building dimensions (40' and 80') to compute ω_{u2}

ω_{u3} - Top of first floor core building

ω_{u4} - Top of first floor windows, core building

ω_{u5} - Top of windows of first floor of fictitious building incorporating the wing.

ω_o - Edge of core building roof

ω_{L1} - Ground line for first floor fictitious building incorporating the wing

ω_{L2} - Outer edge of contaminated strip (intersection with mutual shielding) for use with ground direct, use Z_G and core building dimensions to compute ω_{L2}

ω_{L3} - Ground line for first floor, core building.

ω_s - Mutual shielding, represents limited strip of contamination 50' wide, 80' long. Computed on a basis of $2\,\omega_s$ subtended by 80' x 100' with Z = ½ wall height (= 7' for first floor scatter contribution.)

Mass thickness determinations:

(1) Overhead:

4" Concrete roof	= 1/3 x 150 =	50 psf
6" Floor slab	= 1/2 x 150 =	75
5 ply roof w/gravel	=	7
Total overhead mass thickness		132 psf

(2) Exterior and shear wall:

8" hollow concrete block = 55 psf

(3) Neglect or take as 0 psf: interior partitions and columns, doors, and windows.

b. Fundamental Computations

	E	n	ω	G_d	G_s	G_a
ω_{u_1}	$^{80}/_{120}$ = .67	$^{2x11}/_{120}$ = .183	0.80	-	.21	.054
ω_{u_2}	$^{40}/_{80}$ = .5	$^{2x6.3}/_{80}$ = .157	0.79	-	-	.056
ω_{u_3}	$^{40}/_{80}$ = .5	$^{2x11}/_{80}$ = .275	0.65	-	.31	.074
ω_{u_4}	$^{40}/_{80}$ = .5	$^{2x6}/_{80}$ = .150	0.79	-	.22	.056
ω_{u_5}	$^{80}/_{120}$ = .67	$^{2x6}/_{120}$ = .100	0.89	-	.125	.035
ω_o	$^{40}/_{80}$ = .5	$^{2x21}/_{80}$ = .525	0.41	-	.41	.088
ω_{L_1}	$^{80}/_{120}$ = .67	$^{2x3}/_{120}$ = .050	0.94	.30	.073	- -
ω_{L_2}	$^{40}/_{80}$ = .5	$^{2x.81}/_{80}$ = .021	0.97	.16	-	- -
ω_{L_3}	$^{40}/_{80}$ = .5	$^{2x3}/_{80}$ = .075	0.89	.44	.125	- -
$2 \cdot \omega_s$	$^{80}/_{100}$ = .8	$^{2x7}/_{100}$ = .060	0.86	-	-	- - ω_s = 0.43

B_e(55 psf, 3') = 0.26 $\quad$ B_w(0 psf, 3') = 1.0 $\quad$ E(80' x 120') = 1.38

B_i(55 psf, 3') = 0.26 $\quad$ B_w(0 psf, 19') = 0.65 $\quad$ P_a(1st floor) = $\frac{.15 \times 14 \times p}{6 \times p}$ = .35

B_e(55 psf, 19') = 0.18 $\quad$ S_w(55 psf) = 0.60 $\quad$ $Z_G = {}^{20}/_{70} \times 3$ = .86'

B_o(75 psf) case 3 = 0.021 $\quad$ E (40' x 80') = 1.34 $\quad$ $Z_s = {}^{20}/_{70} \times 22$ = 6.29'

c. Contribution Computations

(1) Roof contribution (neglect roof of wing contribution as being negligible)

$$= C_o(\omega_o, X_o) = C_o(0.41, 132 \text{ psf}) = \underline{\underline{.0078}}$$

(2) Exterior walls contribution sectors (1), (7), (9)
Effective azimuthal sectors:

$$= 53.2^\circ + 20.9^\circ + 84.3^\circ = 158.4^\circ$$

1st floor

$$C_G = \Big[\Big[G_s(\omega_{u_3}) + G_s(\omega_{L_3})\Big] S_w \times E\left(\tfrac{40}{80}\right)$$

$$+ \Big[G_a(\omega_{u_3}) + G_d(\omega_{L_3}3')\Big](1-S_w)\Big] \times B_e(55\text{psf},3')$$

$$-p_a \times B_w(55 \text{ psf}, 3')\Big[G_s(\omega_{u_4})\ S_w \times E\left(\tfrac{40}{80}\right) + G_a(\omega_{u_4})(1-S_w)\Big]$$

$$+ p_a \times B_w(0 \text{ psf}, 3')\ G_a(\omega_{u_4})$$

$$C_G = \Big[\big[.31 + .125\big] \times .60 \times 1.34 + \big[.074 + .44\big] \times .40\Big] \times 0.26$$

$$- .35 \times .26\ \big[.22 \times .60 \times 1.34 + .056 \times .40\big]$$

$$+ .35 \times 1.0\ \big[.056\big] = .145 - .018 + .020 = .147$$

$$\frac{158.4^\circ}{360^\circ} \times .147 = \underline{.0647 = C_G \text{ for 1st floor}}$$

<u>For Azmuthal sectors (1), (7), (9)</u>

2nd floor - 15% aperatures sectors (1), (7), (9)

For Ap = 0%

$$C_G\Big|_o = \Big[\Big[G_s(\omega_o) - G_s(\omega_{u_3})\Big] \times S_w \times E\left(\tfrac{40}{80}\right) + \Big[G_a(\omega_o) - G_a(\omega_{u_3})\Big] \times (1-S_w)\Big]$$

$$\times B_e(55 \text{ psf}, 19') \times B_o(75 \text{ psf})$$

For Ap = 100% $S_w = 0$

$$C_G\Big|_{100} = \left[G_a(\omega_o) - G_a(\omega_{u_3})\right] \times B_w\,(0\text{ psf, }19') \times B_o\,(75\text{ psf})$$

$$C_G\Big|_o = \Big[\left[.41 - .31\right] \times .60 \times 1.34 + \left[.088 - .074\right] \times .40\Big] \times .18 \times .021$$

$$= .0805 + .0056 \times .18 \times .021 = .000326$$

$$C_G\Big|_{100} = \left[.088 - .074\right] \times .65 \times .021 = .000191$$

$$C_G = .85 \times .000326 + .15 \times .000191 = .0003$$

Note: For 2^d floor azimuthal sector (8) may be treated in same manner as sectors (1), (7) and (9).

Thus: $53.2° + 20.9° + 11.4° + 84.3° = 169.8°$

$$.0003 \times \frac{169.8°}{360°} = \underline{.0001 = C_G \text{ for } 2^d \text{ floor}}$$

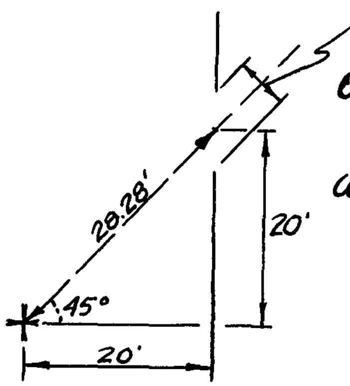
<u>For Azimuthal sectors (1), (7), (8), (9)</u>

Ground contribution of sectors (1), (7), (9) (+ (8), 2nd floor)

$$= .0647 + .0001 = \underline{\underline{.0648}}$$

Note: Contribution of 2d floor essentially neglicible compared to that of 1st floor.

(3) Exterior walls, sectors (3), (8) 1st floor, doorways. Each doorway 7' high x 8' wide.



Projected width of doorway (3)=8'xSin45°=5.66

$$\omega_{(3)}\left(e = \frac{5.66}{7}, n = \frac{2 \times 28.28}{7}\right) = .0070$$

$$\omega_{(8)}\left(e = \frac{7}{8}, n = \frac{2 \times 40}{8}\right) = .0058$$

Case 2 Chart 10

R.F.$_{(3)}$ (ω = .0070) = .0165

R.F.$_{(8)}$ (ω = .0058) = .0145

Contributions of sectors (3), (8) 1st floor = .0310

(4) Exterior wall - Sectors (2), (4), (5), (6) 1st floor

Note: Neglect 2nd floor contribution

Note: Non-wall scattered radiation in sectors (2), (4), and (6) is not mutually shielded so compute separately from non-wall scattered radiation, sector (5).

Note: Scatter radiation in sectors (2), (4), (5), and (6) is mutually shielded so treat as a single case.

Non-wall scattered radiation, sectors (2), (4), (6)
Note: Values same as for sectors (1), (7), (9) 1st floor

$$G_a + G_d = \left[\left[G_a\,(\omega_{u_3}) + G_d\,(\omega_{L_3}, 3')\right] \times (1-S_w)\right] \times B_e(55 \text{ psf}, 3')$$

$$- P_a \times B_w\,(55 \text{ psf}, 3')\left[G_a\,(\omega_{u_4})(1-S_w)\right]$$

$$+ P_a \times B_w(0 \text{ psf}, 3')\left[G_a(\omega_{u_4})\right]$$

$$= \left[\left[.074 + .44\right] \times .40\right] \times .26 - .35 \times .26\left[.056 \times .40\right]$$

$$+ .35 \times 1.0\left[.056\right] = .0535 - .0020 + .0196 = .0711$$

Sectors (2) (4) (6) 13.2° + 8.9° + 33.6° = 55.7°

$\frac{55.7°}{360°}$ x .0711 = .0110 = Contribution of

Non-Wall scattered radiation for 1st floor sectors (2), (4), (6)

Non-wall scattered radiation, sector (5)

Sector (5) mutually shielded at 50'

Note: Neglect 2nd floor contribution

$G_d\,(\omega_{L_3}) - G_d\,(\omega_{L_2}) = .44 - .16 = .28 = \Delta G_d$

$G_a\,(\omega_{u_3}) - G_a(\omega_{u_2}) = .074 - .056 = .018 = \Delta G_a$

Note: Windows entirely in direct-shielded area

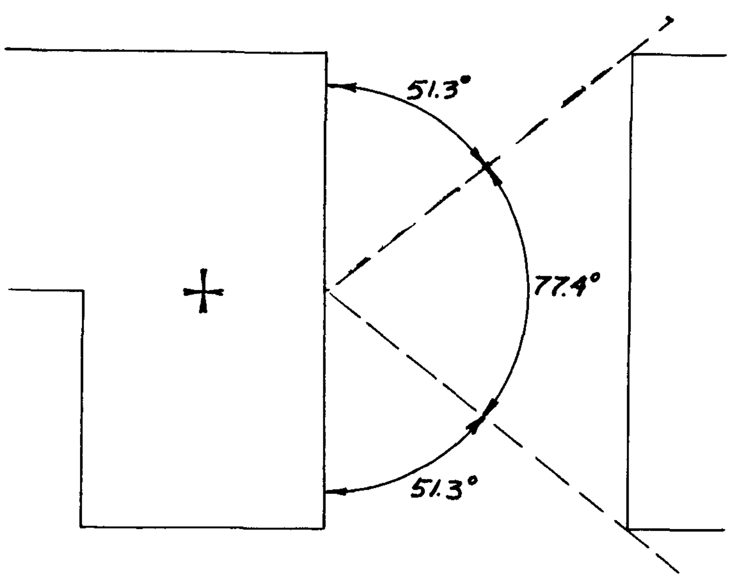
$\left[\Delta G_d + \Delta G_a\right](1-S_w) \;\times\; B_w \quad (55\text{ psf},\ 3') = \left[.28 + .018\right] \times .40 \times .26 = \underline{.0310}$

Sector (5) 59.5°

$\frac{59.5°}{360°} \times .0310 = \underline{.0051 = \text{contribution}}$

<u>for non-wall scattered radiation for 1st floor, sector (5)</u>

Wall-scattered radiation, sectors (2), (4), (5), (6)



Note: 180° contributing radiation scattered by wall, of which 77.4° is mutually shielded. Determine contribution of the limited field 50' x 80' as represented by B_{ws} and of the unshielded wall as represented by B_e and compute a weighted B to be applied to the scatter contribution of the entire wall.

$\left[G_s\ (\omega_{L_3}) + G_s\ (\omega_{u_3})\right] S_w \times E\ (\frac{40}{80})$

$= \left[.125 + .31\right] \times .60 \times 1.34 = .350$

Note: A_p = 15% so only 85% of wall giving scattered radiation.

$.85 \times .350 = .298$

B_{ws} (55 psf, $\omega_s = 0.43$) = .08

B_e (55 psf, 3') = .26

$B = \frac{51.3° + 51.3°}{180°} \times .26 + \frac{77.4°}{180°} \times .08 = .148 + .034 = .182$

Sectors (2), (4), (5), (6) = 13.2 + 8.9 + 59.5 + 33.6 = 115.2°

$\frac{115.2°}{360°} \times .298 \times .182 =$ <u>.0174 = Contribution of wall scattered radiation for 1st floor sectors (2) (4) (5) (6)</u>

(5) Exterior Wall, Wing Sector (10), 63.4°

Interior partition B_i (55 psf, 3')

Neglect 2nd floor exterior wall contribution

$$C_G = \Bigg[\Bigg[\left[G_s(\omega_{u_1}) + G_s\ (\omega_{L_1})\right] \times S_w \times E\ (\frac{80}{120}) +$$

$$+ \left[G_a\ (\omega_{u_1}) + G_d(\omega_{L_1}, 3')\right] \times (1 - S_w)\Bigg] \times B_e \text{ (55 psf, 3')}$$

$$- P_a \times B_w \text{ (55 psf, 3')} \left[G_s(\omega_{u_5}) \times S_w \times E\ (\frac{80}{120}) + G_a(\omega_{u_5})(1 - S_w)\right]$$

$$+ P_a \times B_w \text{ (0 psf, 3')} \left[G_a(\omega_{u_5})\right]\Bigg] \times B_i \text{ (55 psf, 3')}$$

$$= \Bigg[\Bigg[\left[.20 + .073\right] \times .60 \times 1.38 + \left[.054 + .30\right] \times .40\Bigg] \times .26$$

$$- .35 \times .26 \left[.125 \times .60 \times 1.38 + .035 \times .40\right] + .35 \times 1.0 \times .035\Bigg] \times .26$$

$= .0253$

$\frac{63.4°}{360°} \times .0253 = .0045 =$ Contribution of 1st floor exterior walls of sector (10)

d. Contribution Summations

Roof		.0078
Walls:		
Sectors (1), (7), (9) (neglect 2nd floor)		.0647
Sectors (3), (8) (")		.0310
Sectors (2), (4), (5), (6) (")		
(2), (4), (6) Non-wall scattered	.0110	
(5) Non-wall scattered	.0051	
(2), (4), (5), (6) wall scattered	.0174	
		.0335
Sector (10) (Neglect 2nd floor)		.0045
Total, R.F. =		.1415

e. Protection factor = $\frac{1}{R.F.} = \frac{1}{.1415} = 7.1$

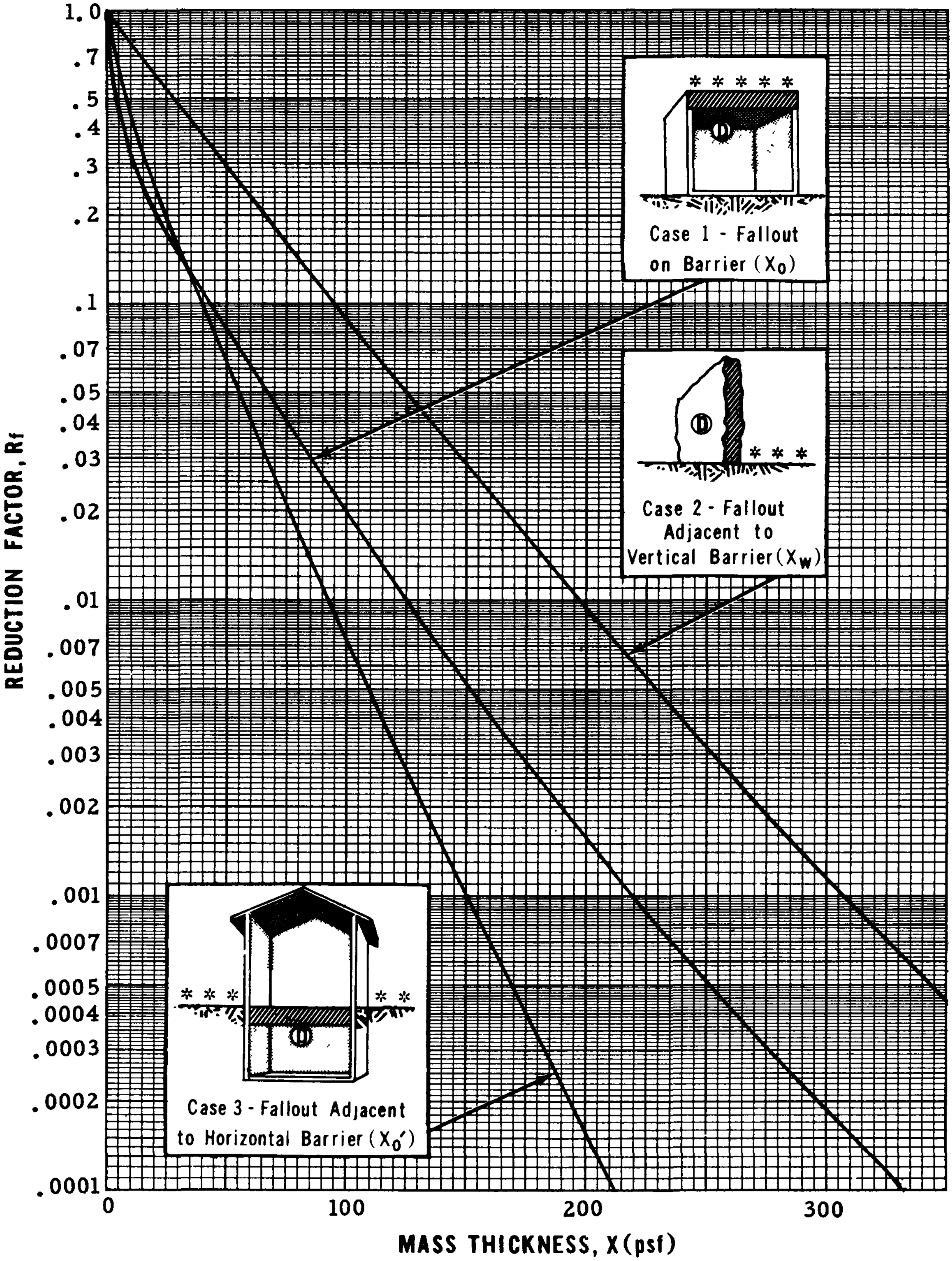


Chart 1. Barrier Shielding Effects (Plane Sources) B_o, B_w and B_o

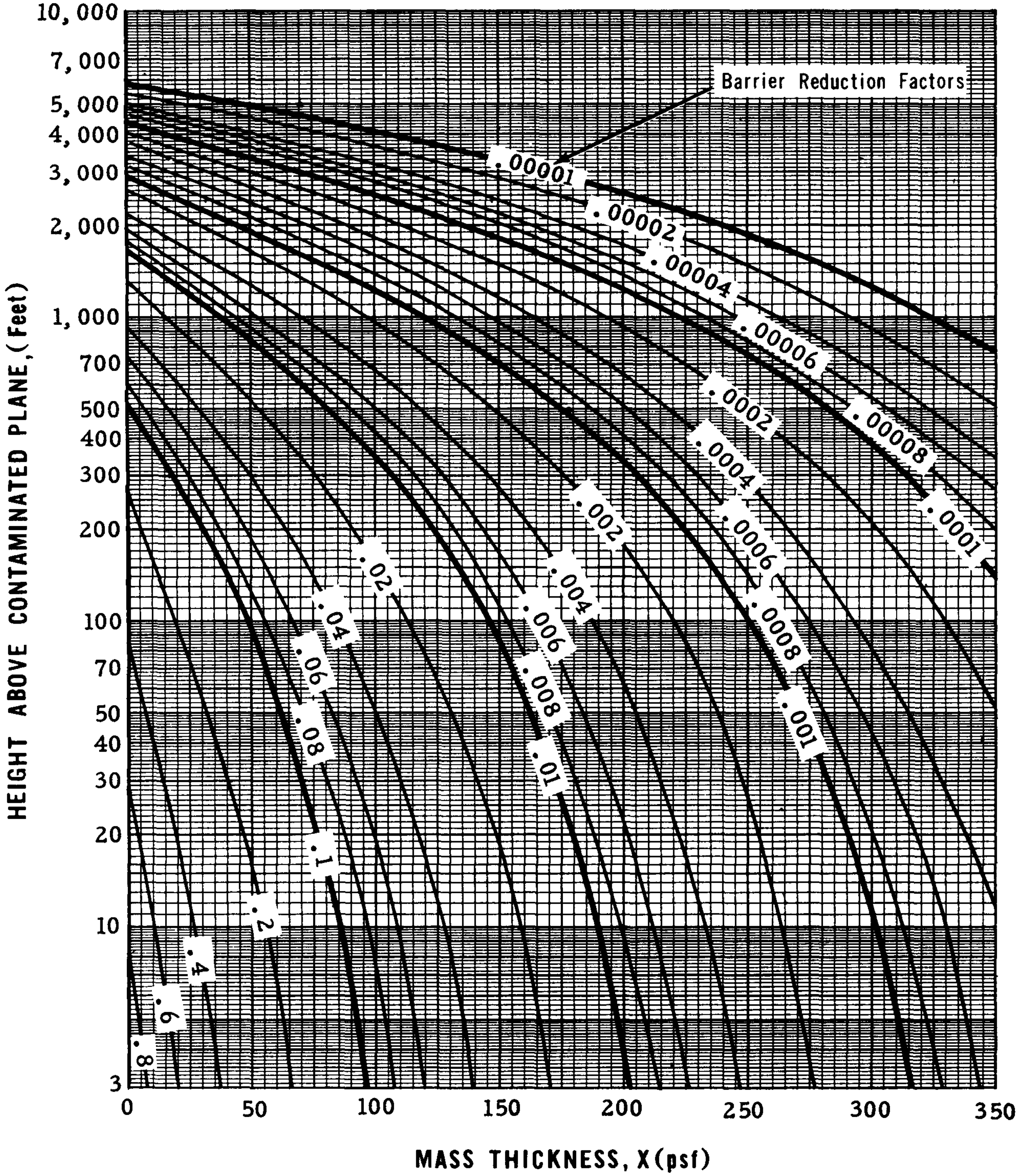


Chart 2. Wall Barrier Shielding Effects for Various Heights, B_w

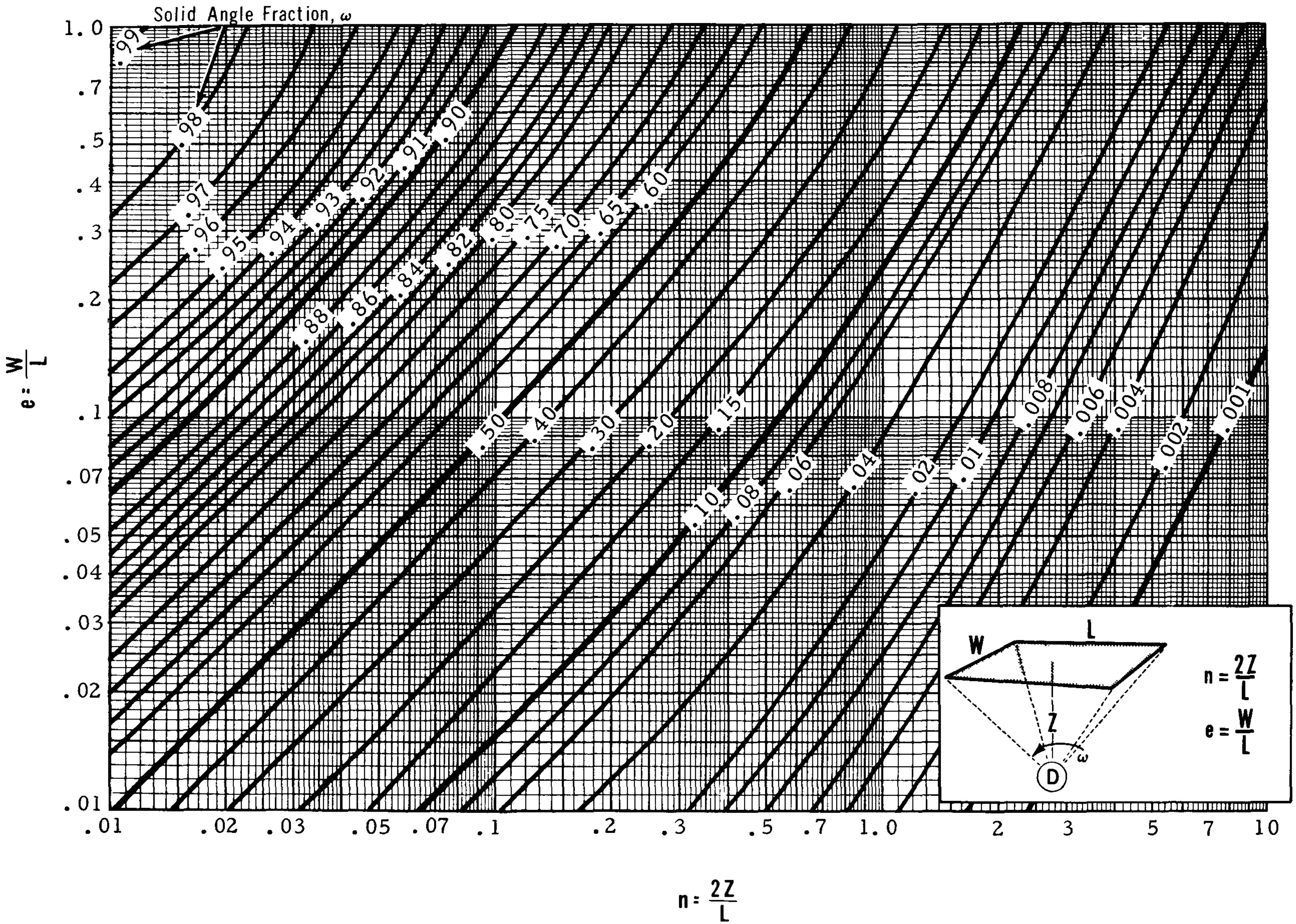
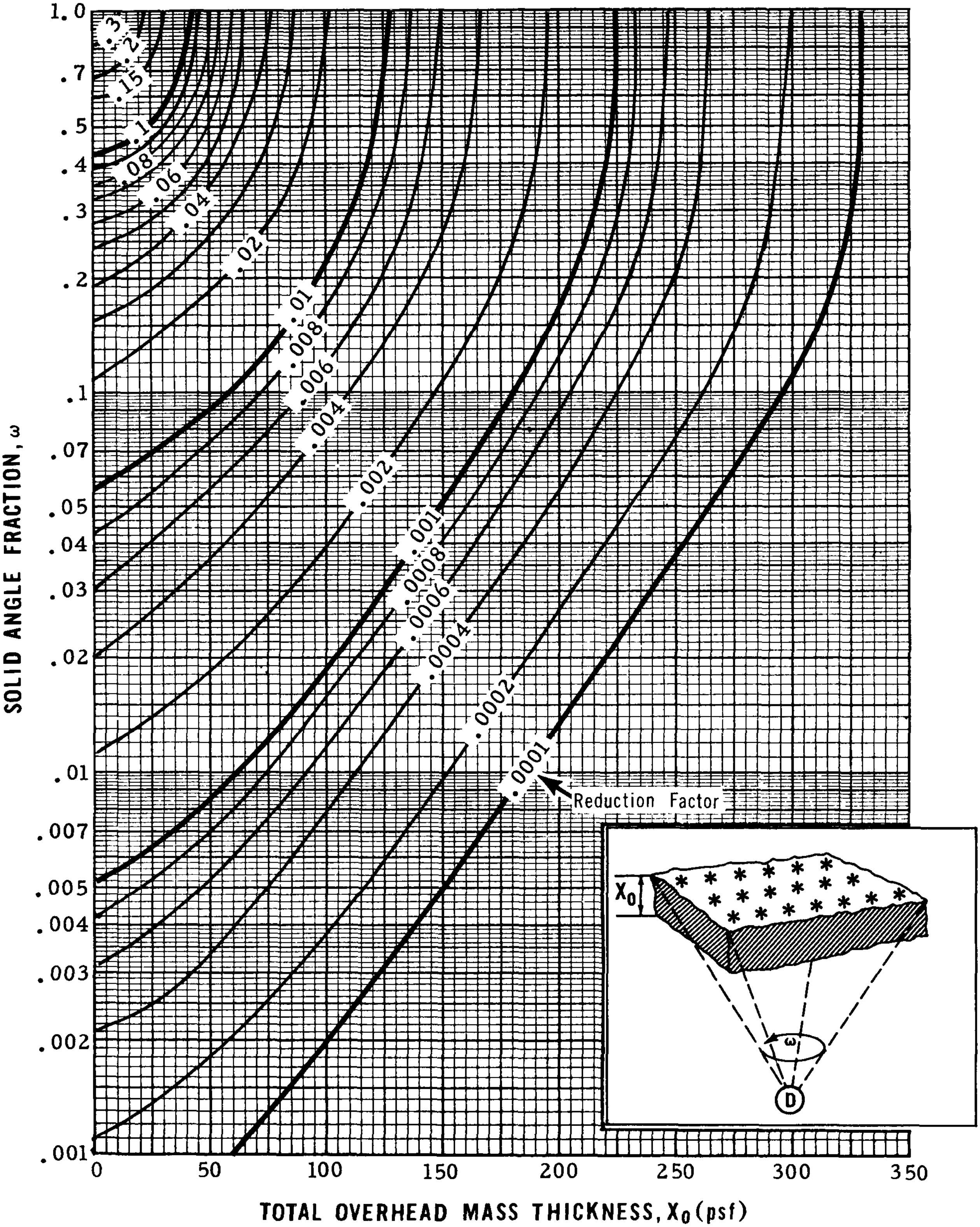


Chart 3. Solid Angle Fraction, ω



note (skyshine not included)

Chart 4. Reduction Factors for Combined Shielding Effects, Roof Contribution, C_o

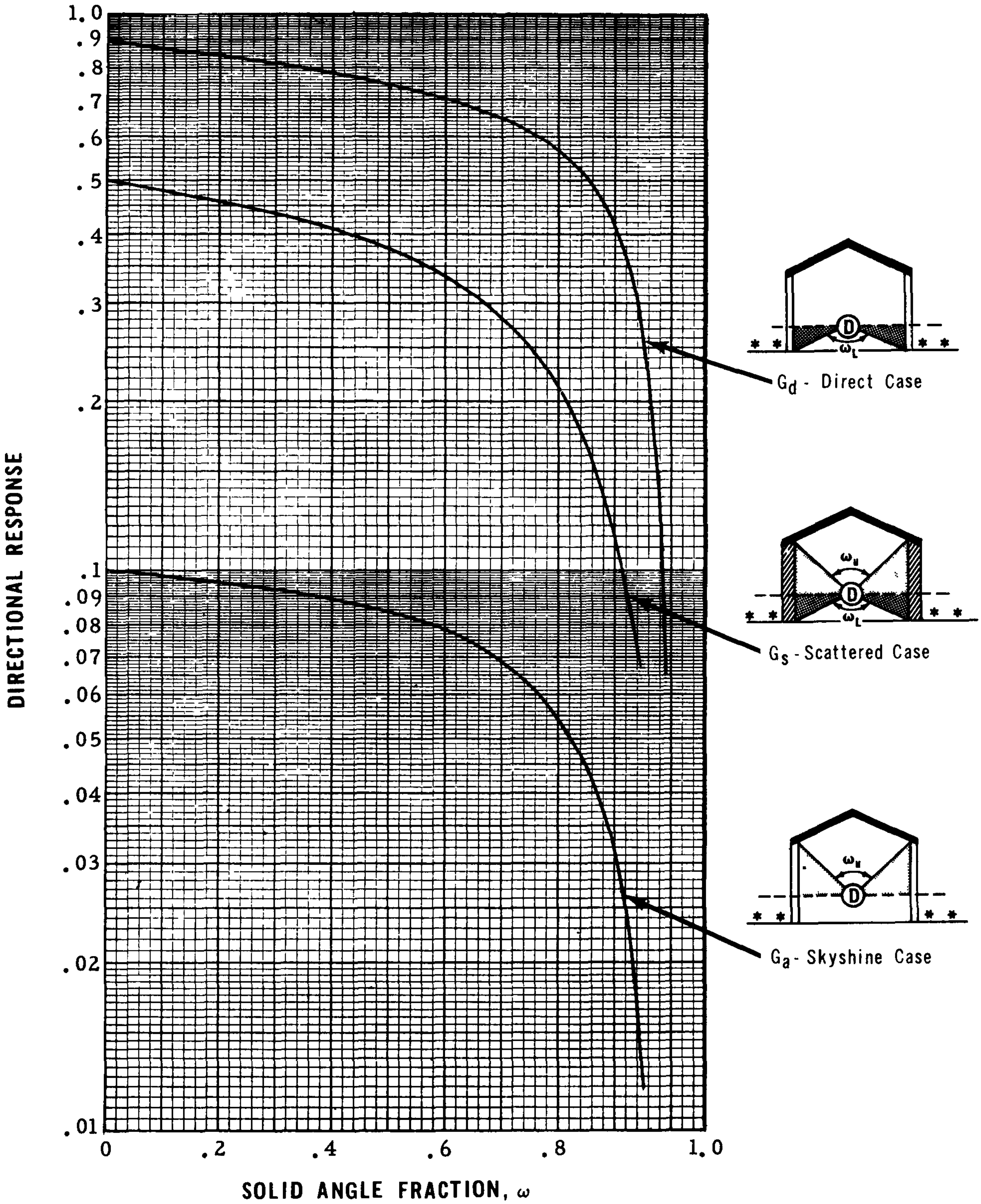


Chart 5. Directional Responses, Ground Contribution, G_d, G_s and G_a

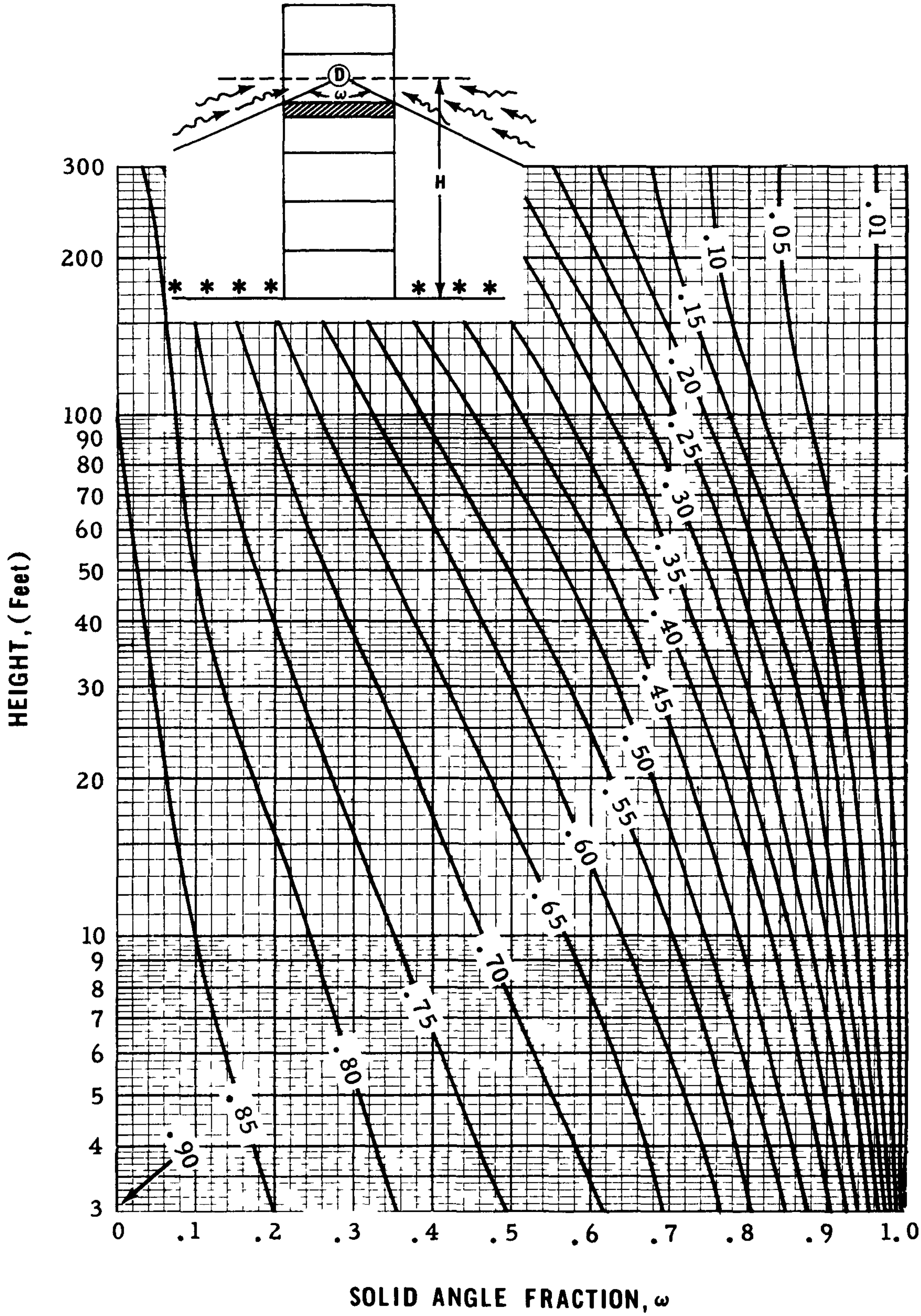


Chart 6. Directional Responses for Various Heights, G_d

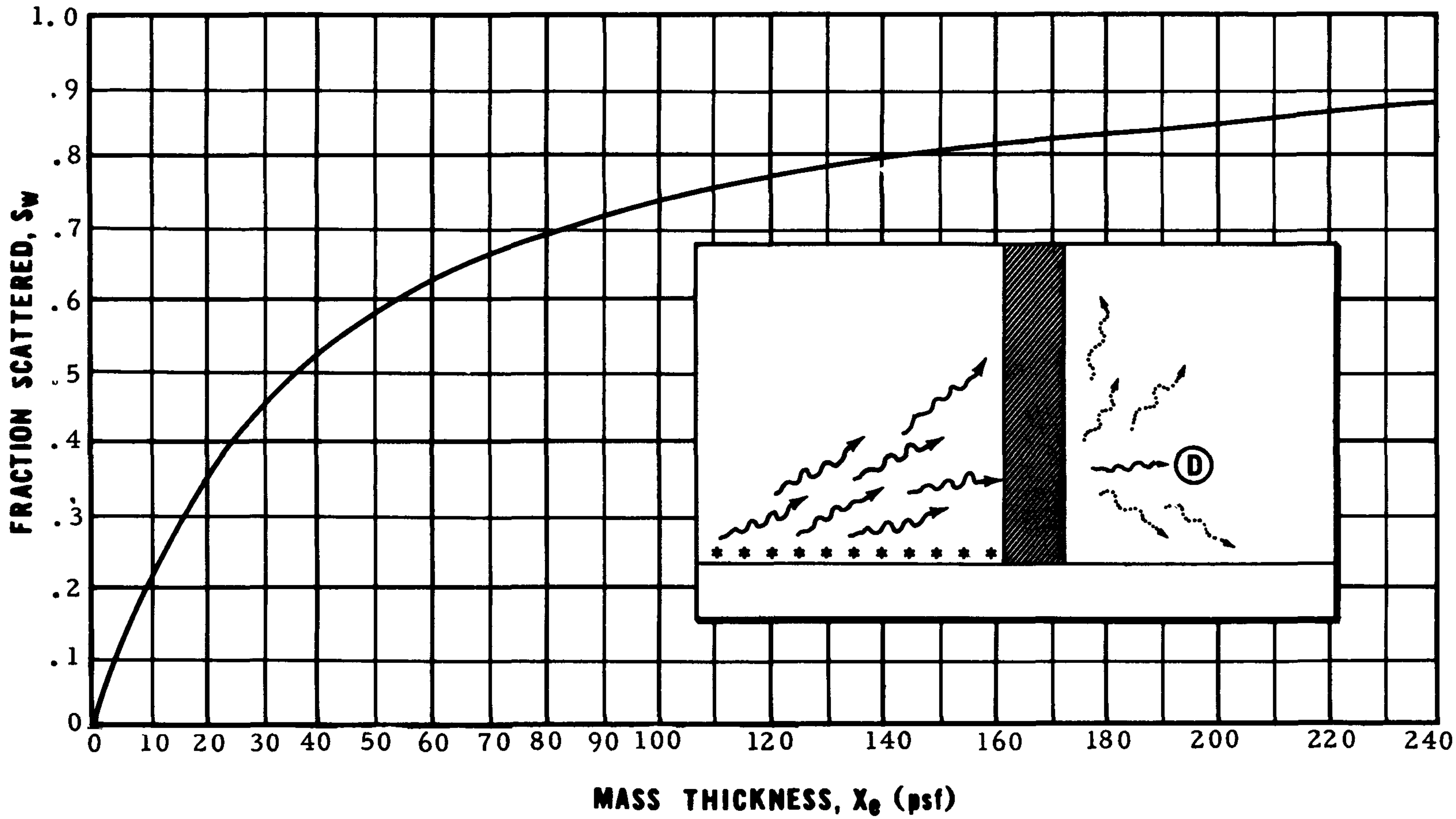


Chart 7. Fraction of Emergent Radiation Scattered in Wall Barrier, S_w

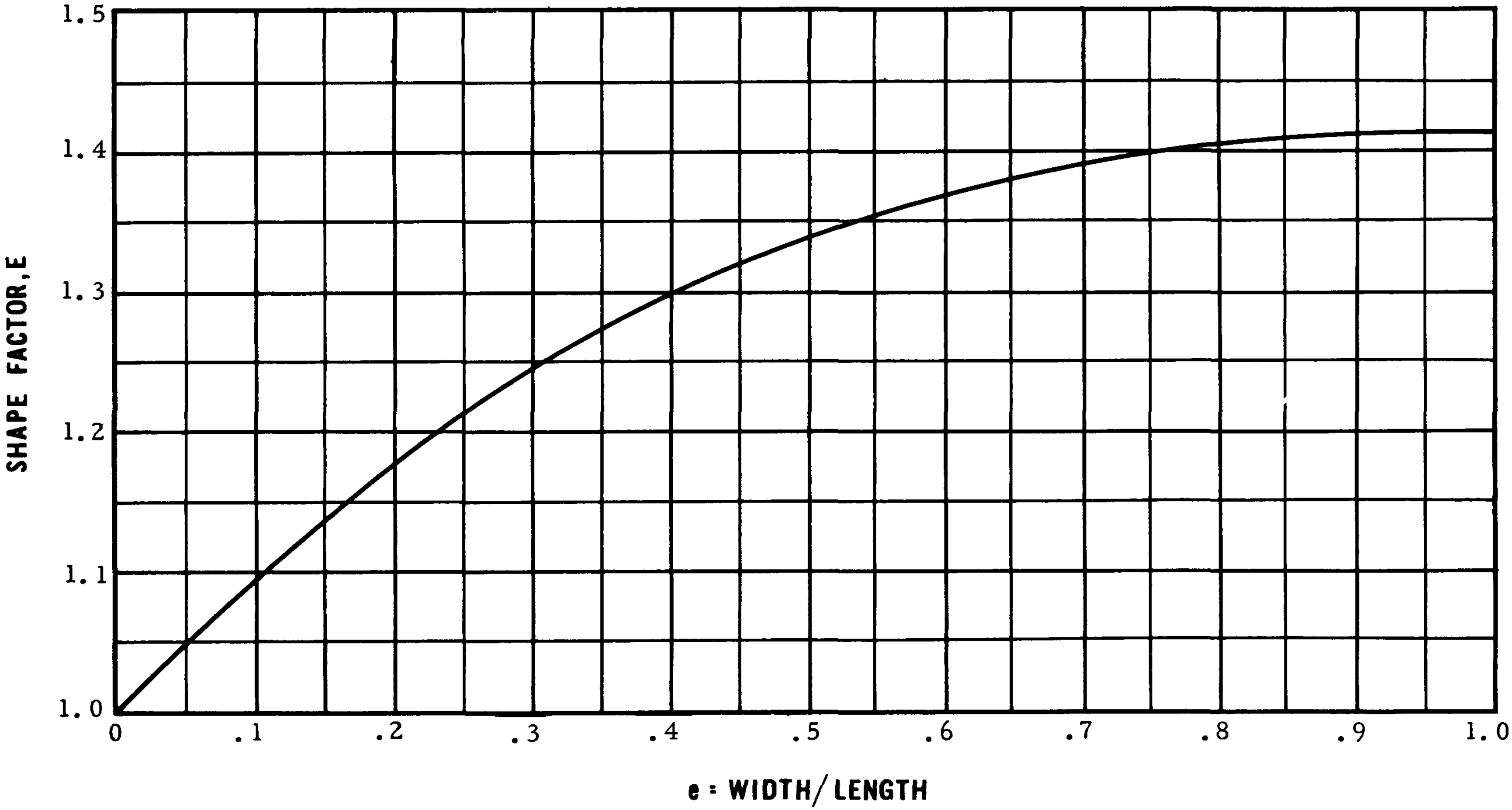


Chart 8. Shape Factor for Wall-scattered Radiation, E

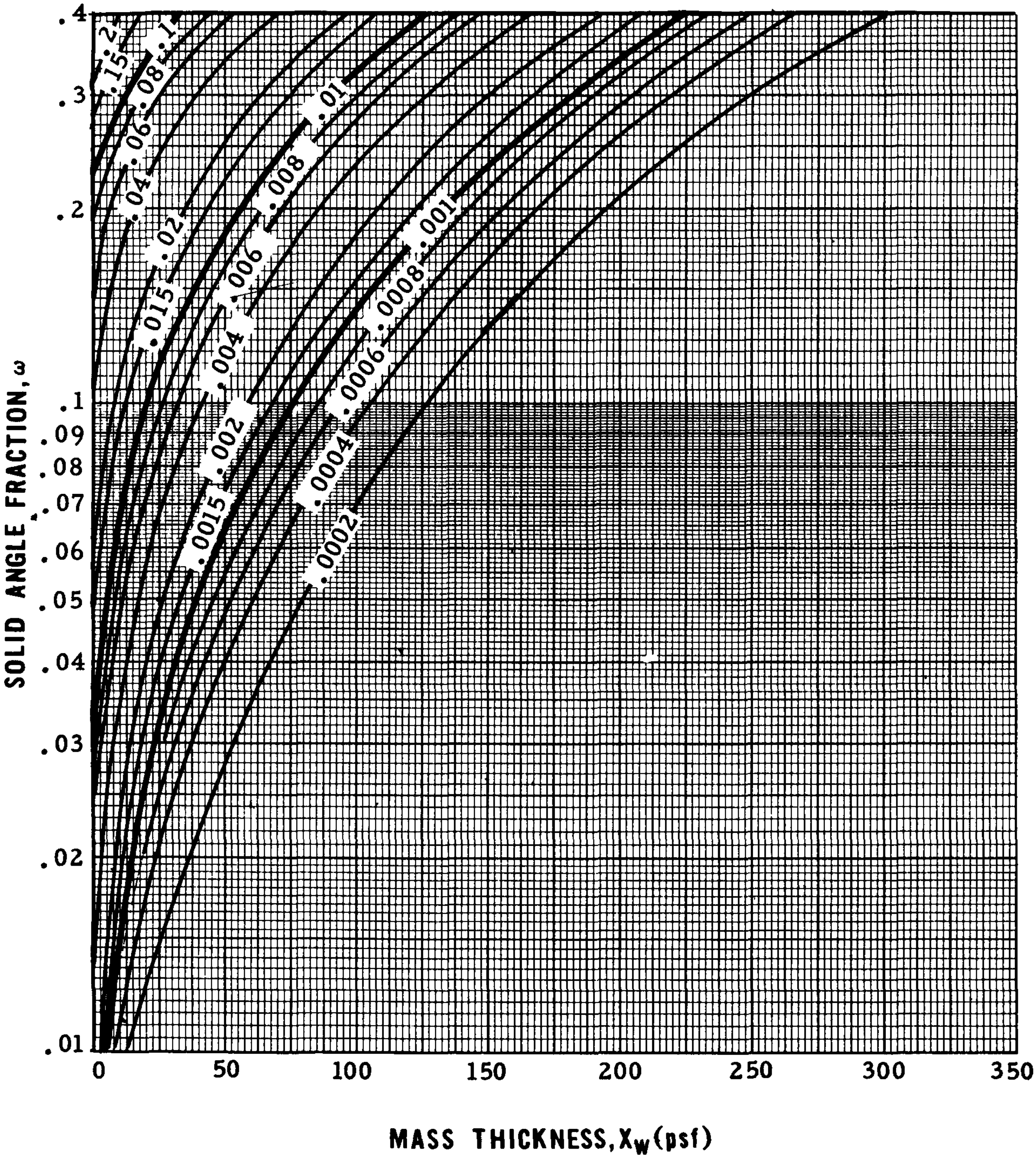


Chart 9. Barrier Reduction Factors for Wall-scattered Radiation for Limited Strip of Contamination

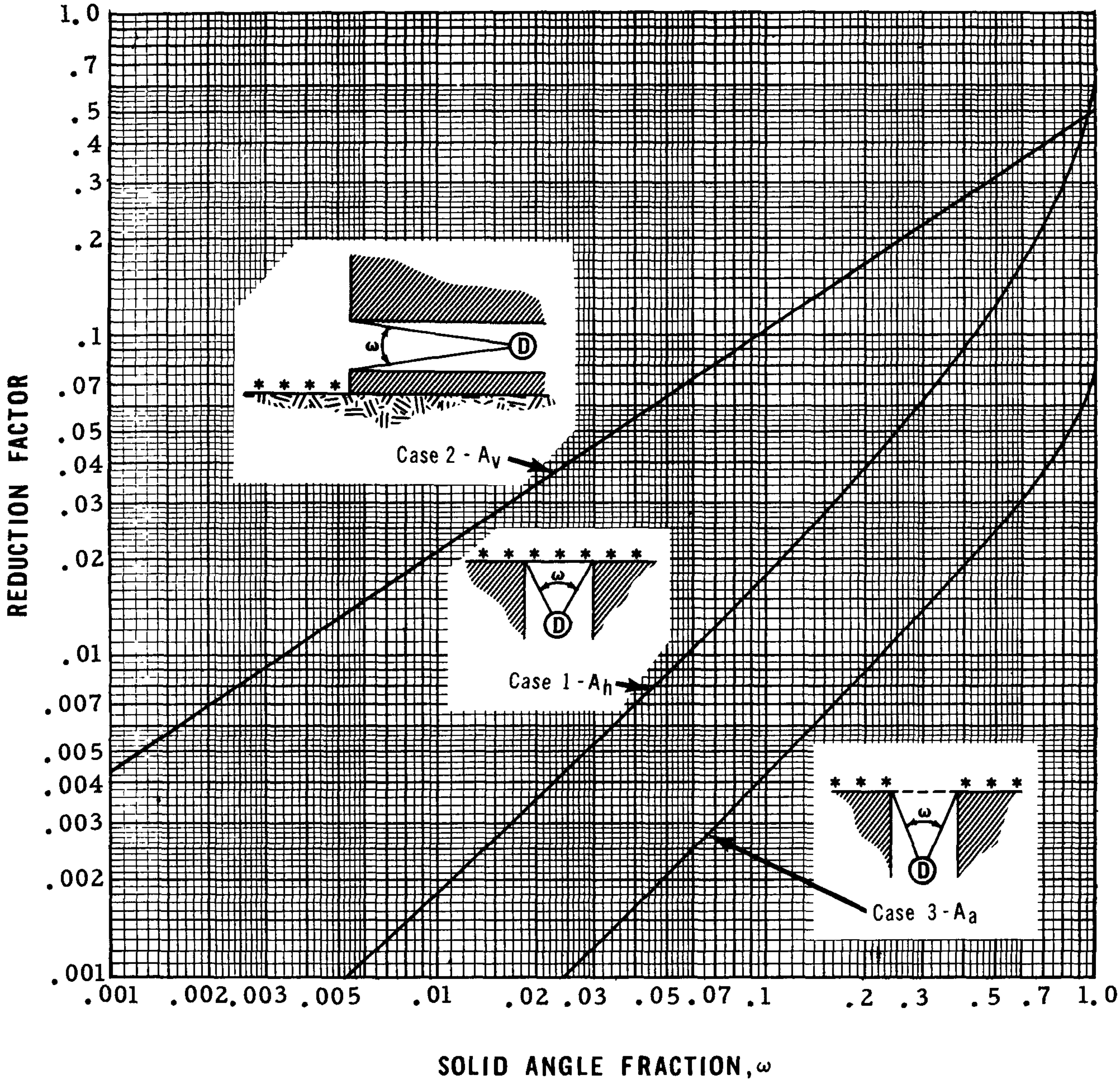


Chart 10. Reduction Factor for Passageways and Shafts

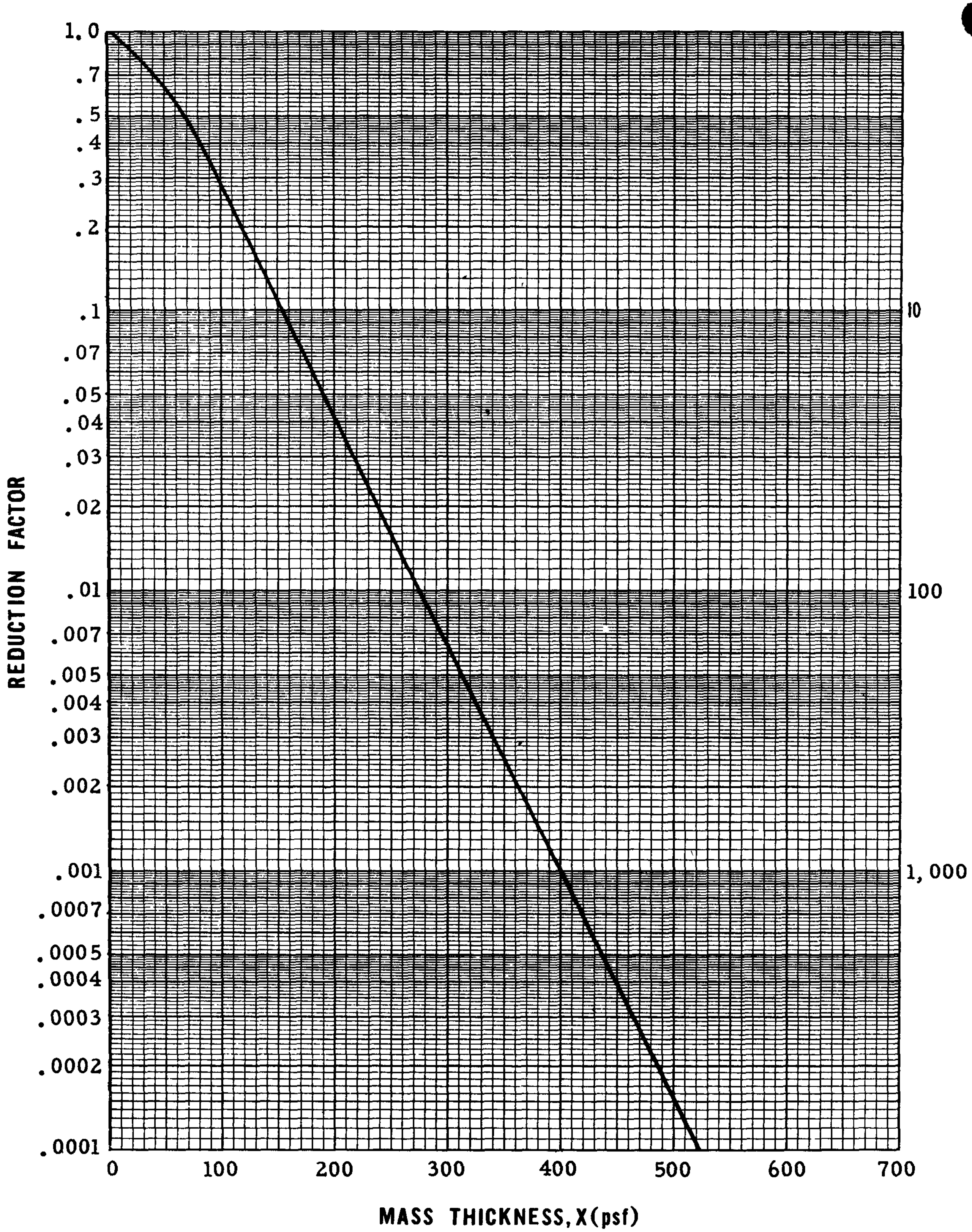


Chart 11. Barrier Shielding Effects (Point Source)